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CONSULTANT REPORT ON EMISSIONS CONTROL OF ENGINE SYSTEMS

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EMISSIONS CONTROL
OF
ENGINE SYSTEMS

CONSULTANT REPORT TO THE:
Committee on Motor Vehicle Emissions
Commission on Sociotechnical Systems
National Research Council

SEPTEMBER 1974

U.S. ENVIRONMENTAL PROTECTION AGENCY
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An evaluation was made of the potential of conventional, spark-ignition internal-combustion engines and other internal-combustion engines, such as rotary, diesel and stratified-charge engines, for meeting strict levels of oxides of nitrogen emissions control in conjunction with specified levels of unburned hydrocarbon and carbon monoxide emissions. The potential of alternative, more advanced automotive engines, such as the gas turbine, Stirling, and Rankine power plants, for meeting similarly strict levels of emissions control were assessed.

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CONSULTANT REPORT

to the

Committee on Motor Vehicle Emissions

Commission on Sociotechnical Systems

National Research Council

on

EMISSIONS CONTROL OF ENGINE SYSTEMS

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September 1974

NOTICE

This consultant report was prepared by a Panel of Consultants at the request of the Committee on Motor Vehicle Emissions of the National Academy of Sciences. Any opinions or conclusions in this consultant report are those of the Panel members and do not necessarily reflect those of the Committee or of the National Academy of Sciences.

This consultant report has not gone through the Academy review procedure. It has been reviewed by the Committee on Motor Vehicle Emissions only for its suitability as a partial basis for the report by the Committee.

The findings of the Committee on Motor Vehicle Emissions, based in part upon material in this consultant report but not solely dependent upon it, are found only in the *Report by the Committee on Motor Vehicle Emissions* of November 1974.

PREFACE

The National Academy of Sciences, through its Committee on Motor Vehicle Emissions (CMVE), initiated a study of automobile emissions-control technologies at the request of the United States Congress and the Environmental Protection Agency (EPA) in October 1973. To help carry out its work, the CMVE engaged panels of consultants to collect information and to prepare consultant reports on various facets of motor vehicle emissions control. This Consultant Report on Emissions Control of Engine Systems is one of five consultant reports prepared and submitted to the Committee in connection with the Report by the Committee on Motor Vehicle Emissions of November 1974. The other consultant reports are:

> An Evaluation of Catalytic Converters for Control of Automobile Exhaust Pollutants, September 1974
>
> Emissions and Fuel Economy Test Methods and Procedures, September 1974
>
> Field Performance of Emissions-Controlled Automobiles, November 1974
>
> Manufacturability and Costs of Proposed Low-Emissions Automotive Engine Systems, November 1974

These five consultant reports are NOT reports of the National Academy of Sciences or its Committee on Motor Vehicle Emissions. They have been developed for the purpose of providing a partial basis for the report by the Committee as described more fully in the cover NOTICE.

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CONCLUSIONS

1. From the viewpoint of fuel economy, at least on an urban-type driving cycle, the diesel and stratified-charge engines appear most attractive. Potential problem areas for these engines that must be resolved before large-scale introduction include smoke and particulates (and possible adverse health effects), odor, noise and a lower performance than a conventional spark-ignition (S.I.) engine due to lower power-to-weight ratio (especially with the diesel).

2. The three-way catalyst system with feedback control appears to offer benefits as far as maintainability and driveability are concerned, with only slight loss of fuel economy due to emissions control. The dual-catalyst (Gould) system provides a tolerable interim approach until the three-way catalyst, feedback system is ready for production.

3. Regarding standards for 1978, lowering of NO_x emissions levels from 1.0 to 0.4 g/mi appears to exact a penalty in fuel consumption of up to 35% by excluding the diesel engine. Possible benefits to health should be weighed against this cost.

4. There are no alternative, non-internal combustion engines that could be available in mass production for standard-size automobiles before the 1980's.

5. The accompanying table summarizing the work of the Panel of Consultants on Internal Combustion Engines presents emissions levels achievable in certification for various systems, as well as fuel economy penalty (or advantage) due to emissions controls as measured on the Federal CVS/CH driving cycle. Projected dates of availability for mass production of each system are also given in the table.

Emissions Levels	System	Fuel Economy Penalty (relative to 1967)	Availability for Mass Production
0.41-3.4-2.0	Oxidation catalyst and exhaust gas recirculation and engine modifications	5%	1976
	Lean burn engine	5%	1977
	Diesel	-(25%-40%)	Now
	Stratified charge - small volume prechamber with reactor	0%-10%	Now
	Stratified charge - direct fuel-injected with catalyst	-(25%-40%)	1980
	Wankel with lean reactor	5%-10%	1976
0.41-3.4-1.0	Diesel and exhaust gas recirculation	-(20%-35%)	1976
	Dual catalyst (e.g., Gould) system	5%-10%	1977
	Three-way catalyst and feedback	0%-5%	1978-80
	Stratified charge - small volume prechamber with reactor	10%-20%	Now
	Stratified charge - direct fuel-injected with catalyst	-(15%-20%)	1980
	Wankel with lean reactor and exhaust gas recirculation	20%	1976
0.41-3.4-.4	Dual catalyst (e.g., Gould) system	5%-10%	1977
	Three-way catalyst and feedback	0%-5%	1978-80
	Stratified charge - small volume prechamber with reactor	25%-30%	Now
	Stratified charge - direct fuel-injected with catalyst	0	1980

1. INTRODUCTION

The Consultant Report on Emissions Control of Engine Systems represents the findings of the Panel on Internal Combustion Engines and the Panel on Alternative Engines. The first Panel was charged with evaluating the potential of conventional, spark-ignition internal-combustion engines and other internal-combustion engines, such as the rotary, diesel and stratified-charge engines, for meeting strict levels of oxides of nitrogen (NO_x) control in conjunction with specified levels of unburned hydrocarbons (HC) and carbon monoxide (CO). The second Panel was charged with assessing the potential of alternative, more advanced automotive engines, such as the gas turbine, Stirling, and Rankine power plants, for meeting similarly strict levels of emissions control. Primary consideration was to be given to cost, in terms of fuel consumption, associated with the achievement of various NO_x levels by the different engine systems. The Panels were to be concerned with emissions levels attainable in certification with vehicles tested according to the 1975 Federal Test Procedure (FTP). Durability of the engine - and emissions-control systems for 50,000 miles was of importance, with mileage accumulation according to the certification test procedure. Likewise, fuel economy was to be evaluated on vehilces being driven on the FTP. Other Consultant Reports to the CMVE are to deal with performance in customer use, alternate testing procedures, catalytic converters, and the manufacturability and costs of low-emissions engine systems.

The CMVE, for the purpose of this study, is interested in engines and systems that could be available in mass production by the late 1970's and early 1980's.

For the 1975 model year, well over 95% of the new vehicles sold in the United States will continue to be powered by conventional, reciprocating spark-ignition engines with add-on devices to control emissions to the required levels. Small numbers of rotary, stratified-charge and diesel-powered vehicles will also be available. Due to manufacturing lead times and constraints in the tooling industry, it is clear that the conventional engine will continue to dominate the market, at least up to the 1980's, in spite of potential advantages that one or the other alternatives may have in terms of emissions, economy, maintainability, performance or cost. For this reason, the first sections of this report will deal with the conventional engine, and the various add-on devices and engine modifications that have the potential for meeting increasingly stringent NO_x levels. Later sections of the report will cover, in depth, the rotary, stratified-charge and diesel internal combustion engines.

The current status of development of alternative, non-internal-combustion engines is such that at least another generation of development will be required before any of these will have reached the stage of being considered a suitable prototype for manufacture. Whereas several such engines have been run in automobiles; for example, the gas turbine, Stirling, steam and electric engines, several major developments are necessary before these power plants would be ready for mass production. The Panel of Consultants estimates that 1982 is the earliest one of the alternate engines, the gas turbine, would be ready for limited production, and even then only if several technological advances are achieved. For this reason, the sections of this report dealing with alternative engines must be considered of less direct relevance to the goals of the CMVE in their study as compared to the sections on the internal-combustion engine.

2. MODIFICATIONS TO CONVENTIONAL RECIPROCATING SPARK-IGNITION (S.I.) ENGINES

Up to the 1974 model year, auto manufacturers for the most part have met the exhaust-emissions standards by means of modifications to the conventional engine. As a reference, the federal and California standards that have been achieved in certification, all converted to the 1975 FTP, as well as future emissions standards, are given in Table 2.1. Changes to achieve the specific standards, up to model year 1974, have included alterations in spark timing, reduction in compression ratio (CR), use of leaner air/fuel (A/F) ratios, shorter choke times, improvements in carburetion, exhaust-gas recirculation (EGR), use of air pumps and air injection to promote exhaust reactions, and inlet air preheating. The primary effects of these modifications on exhaust emissions are summarized in Table 2.2 below.

Such techniques have been successful in achieving reductions in exhaust emissions from those of an uncontrolled 1967 vehicle of approximately 80% in hydrocarbons, 70% in carbon monoxide and 50% in oxides of nitrogen. Accompanying these reductions in emissions has been an increase of vehicle fuel consumption. Factors such as spark retard, reduction of compression ratio and exhaust-gas recirculation have tended to reduce engine efficiency and, hence, degrade fuel economy. Alternately, reductions of choke times and improvements in carburetion have a beneficial effect on fuel economy.

The overall fuel economy degradation on a sales-weighted average due to emissions controls, from 1967 to 1973 or 1974, is between 10%-15%[1,2,3*] based on the vehicles being tested on the urban federal driving cycle. Greater losses have been felt in larger cars, only small decreases or even benefits in smaller cars.

There are several reasons why small cars have not shown the same increase of fuel consumption as standard or large-size cars. First, with the lower exhaust flows of smaller cars, the mass emissions of NO_x and CO of uncontrolled small cars (less than 3,000 lbs) were less than those of larger cars (greater than 4,000 lbs).[4] This

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*References are listed at the end of the report (page 139).

TABLE 2.1

Federal Exhaust-Emission Standards

	HC(g/mi)	CO(g/mi)	NO$_x$(g/mi)
1967 (Precontrol)	12	79	6
1968	6.2	51	NR*
1970	4.1	34	NR
1972	3	28	NR
1973,1974	3	28	3.1
1975,1976	1.5	15	3.1
1977	0.41	3.4	2.0
1978	0.41	3.4	0.4

*Not required

California Exhaust-Emission Standards

1972	2.9	28	3.1
1974	2.9	28	2.0
1975,1976	0.9	9	2.0

TABLE 2.2

Effect of Engine Modifications on Emissions

	HC	CO	NO_x
Spark Retard	Reduce	----	Reduce
Reduce CR	Reduce	----	Reduce
Lean A/F	Reduce	Reduce	Increase (then decrease if beyond A/F = 16)
EGR	Increase	----	Reduce
Air Injection	Reduce	Reduce	----
Shorter Choke Time	Reduce	Reduce	----
Air Preheat	Decrease	----	Increase

has meant that less EGR, for example, has been necessary to reduce NO_x to required levels.

Further, pre-controlled small cars typically ran with richer calibrations than standard or large cars. Greater improvements were then realized with leaning out the carburetion. Finally, fuel-metering technology for larger cars has been superior to that of small cars. The imposition of emissions controls has required large improvements in fuel metering for small cars, some manufacturers going to mechanical or electronic fuel injection. Thus, these factors have all tended to improve economy of small cars, canceling out losses due to other engine modifications to achieve emissions control.

The most important factors that cause increased fuel consumption due to emissions control have been spark retard, decrease of compression ratio, and EGR. Reduction of one compression ratio, for example from 9:1 to 8:1, has the effect of increasing fuel consumption by 3%-5%. A comparable fuel economy penalty has been incurred with the use of spark retard to achieve HC and NO_x control. Further, the use of off/on EGR to achieve NO_x levels of 3.1 g/mi called for in 1973 and 1974 models has brought about an approximate 5%-6% decrease of fuel economy.

It is important to realize that exhaust emissions are influenced by many engine variables; for good economy and low emissions, control systems must be optimized. For example, running lean provides benefits in fuel economy, but may result in higher NO_x emissions, necessitating the use of EGR. The use of EGR, requiring mixture enrichment to retain driveability, also permits an increase of spark advance, which may recover some of the fuel economy degradation caused by using EGR.[5]

In general, engine modifications, such as spark retard and EGR or the addition of an air pump, adopted to lower emissions from 1974 levels to those of 1975 models for the 49 states or even

California, have the effect of degrading both fuel economy and driveability. Thus, whereas manufacturers are certifying some vehicles with only engine modifications for production at 1975 federal levels or at 1975 California levels, such vehicles incur a fuel economy penalty of 5%-10% relative to 1974 vehicles. For the most part, such systems are backup to their primary, first-choice system which features the use of an oxidizing catalytic converter.

3. CONVENTIONAL SPARK-IGNITION ENGINE WITH OXIDATION CATALYST - 1975 STANDARDS

A very large percentage of 1975 models sold in the United States, both domestic and foreign made, will feature the use of an oxidation catalyst to clean up the exhaust hydrocarbons and carbon monoxide. Several different configurations of catalyst and system will be used. For example, General Motors will generally employ an under-floor pelletized catalyst bed, whereas Ford will use a monolith located nearer to the engine. Ford will use an air pump on all catalyst-equipped cars; General Motors and Chrysler will use air pumps in California cars, but only on a small number of 49-state cars. Whereas Chrysler and Ford will use about the same carburetion as 1974, General Motors will run at about A/F ratio = 16, leaner than 1974. All catalyst-equipped cars will use low lead (91 RON) fuel (.05 g/gal) to prevent catalyst poisoning. Nineteen seventy-five emissions-control systems will also feature improved start-up procedures to permit rapid fuel evaporation, high energy breakerless electronic ignition to provide more reliable ignition, and EGR to control NO_x.

At present, it appears that virtually all 1975 models equipped with oxidizing catalytic converters will be certified for production. Catalyst durability is such that no American-made models and only some European models will require catalyst changes in 50,000 miles. With lead-free fuel and breakerless ignition, there appears to be very little deterioration in engine emissions for 50,000 miles. The chief difficulty is deterioration in HC control with the catalytic converter. Whereas HC conversion efficiencies are well over 95% at low mileage, they deteriorate to 60%-70% at 50,000 miles.

Fuel-economy gains are to be experienced with the use of oxidation catalysts. To some extent, the car can now be tuned for optimum economy, with the catalyst cleaning up the resultant HC and CO emissions, rather than tuning for minimum emissions and losing economy. Chief economy gains are to be realized with elimination of some of the spark retard used in previous model years to control HC. The limitation on the amount of spark advance with catalytic systems is not resultant HC levels but the octane rating of the fuel used and the resultant problem of knock. With more spark advance, proportional EGR systems more closely tailored to the engine requirements, better cold-start performance and, in some cases, leaner-carburetion, large economy improvements are possible. On the basis of data taken from durability certification cars, General Motors[6] reports the following improvements in fuel economy, comparing 1975 vs 1974 49-state cars in the federal test procedure:

Including Mix Change	+ 19.8%
Eliminating Mix Change*	+ 21.1%

*Assumes 1975 mix (75% large cars) for 1974 production, where actual 1974 production was 80% large cars.

A comparison of fuel economy for GM California 1975 cars vs 49-state cars shows an approximate 5% degradation in fuel economy sales-weighted miles per gallon (SWMPG) for the California cars, due primarily to the use of the air pump and increased EGR in California cars. Again, results are from certification tests run on the FTP.[6]

Somewhat lesser fuel economy improvements in certification have been reported by the other American and foreign manufacturers. For example, Chrysler and Ford anticipate a 5% improvement in economy over 1974 vehicles. It must be remembered that the above figures represent comparisons between different model years of the same manufacturers. Comparisons of the SWMPG of American manufacturers for 1974 models showed the following:[7]

GM	10.29
Ford	11.63
Chrysler	11.10

The use of catalytic converters on small cars has not resulted in a fuel economy improvement, primarily because such cars did not suffer the penalty due to engine modifications of the large cars. Therefore, foreign manufacturers report fuel economy for 1975 vehicles roughly equivalent to that of 1974 models.

It is significant to note that with the use of the catalytic converter, most, if not all, of the 10% to 15% fuel economy penalty attributed to emissions controls has been recovered.

4. POTENTIAL OF CONVENTIONAL ENGINES WITH OXIDATION CATALYSTS

In examining the potential of conventional systems for meeting the current 1977 standards of 0.41 g/mi HC, 3.4 g/mi CO and 2.0 g/mi NO_x, it is of interest to look first at results achieved by 1975 California certification cars, tuned to meet levels of 0.9 g/mi HC, 9.0 g/mi CO and 2.0 g/mi NO_x. Table 4.1 shows data from all the vehicles that have, at this date, been made available to the Panel of Consultants and have completed California certification. The quoted emissions values include 50,000-mile deterioration factors, applied in the required certification test procedure.[8]

Caution must be exercised in drawing conclusions from Table 4.1; manufacturers must aim at targets well below the standards to ensure with some degree of confidence that a satisfactory mix of vehicles will pass certification and be available to the market. Nevertheless, these vehicles were not tuned to meet 1977 levels, but rather the higher California 1975 levels, so significant reduction in emissions are possible (below those of Table 4.1).

Very little data are available on systems tuned to meet 1977 levels. General Motors has had two fleets of Oldsmobiles in service with the California Highway Department. Both fleets were tuned to meet 1977 levels, and equipped with oxidation catalysts, one fleet with air pumps, one without. Results are shown in Table 4.2. Mileage accumulation for these data were not according to the AMA durability schedule of the FTP.

The data shown in the above mentioned tables provide convincing evidence that 1977 levels can be achieved by model year 1977. One method of achieving the required reductions in emissions from California 1975 certification would be via engine modifications, such as spark retard, with the loss of fuel economy. However, improvements are available which would not necessarily increase fuel consumption over that of a 1975 California car.

TABLE 4.1

Results of 1975 California Certification

Manufacturer		Vehicle	HC	CO	NO_x	MPG
1.	GM	Vega, 2,750# I.W., 140 CID Automatic	0.4	6.8	1.6	20.1
2.	GM	Cutlass, 4,500#, 350 CID, Automatic	0.4	2.3	1.4	12.6
3.	GM	Delta 88, 5,000#, 350 CID	0.7	6.7	1.6	12.4
4.	AMC	Hornet 232 A, 3,500#	0.28	7.5	1.5	15.6
5.	AMC	Hornet 258 A, 3,500#	0.18	5.9	1.5	14.4
6.	AMC	Hornet 232 M, 3,500#	0.46	7.3	1.9	13.8
7.	AMC	Gremlin 232 A, 3,000#	0.22	6.2	1.5	16.8
8.	AMC	Pacer 258 M, 3,500#	0.26	6.3	1.9	14.9
9.	AMC	Matador 304 A, 4,500#	0.46	3.7	1.9	13.1
10.	AMC	Gremlin 304 M, 3,500#	0.49	6.3	1.7	13.0
11.	AMC	Hornet 304 M, 3,500#	0.64	7.4	1.9	12.8
12.	AMC	Matador 304 A, 4,500#	0.23	3.6	1.9	12.3
13.	AMC	Matador 2V-360 A, 4,500#	0.51	4.3	2.0	11.9
14.	AMC	Matador 2V-360 A, 4,500#	0.36	3.2	1.9	11.9
15.	AMC	Matador 2V-360 A, 4,500#	0.45	2.9	1.6	11.6
16.	AMC	Matador 4V-360 A, 4,500#	0.42	2.6	1.9	11.7
17.	AMC	Matador 4V-401 A, 4,500#	0.51	3.8	1.4	10.4

REFS. 9, 10

TABLE 4.2

Exhaust Emission Test Summary
California Division of Highways
Underfloor Converter Fleet

13 Oldsmobiles (No air pumps)

Average Test Mileage	No. of Cars	1975 EPA Grams/Mile[1]		
		HC	CO	NO_x
194	13	0.19	1.90	1.75
4108	13	0.20	2.22	1.86
8222	13	0.24	2.14	1.84
12296	5	0.25	2.83	1.75
16022	13	0.24	2.87	1.79
20535	5	0.23	2.13	1.72
24976	3	0.21	3.16	1.93
24950[2]	12	0.23	2.12	1.86
29635	2	0.19	2.23	2.20

12 (AIR) Oldsmobiles

Average Test Mileage	No. of Cars	1975 EPA Grams/Mile[2]		
		HC	CO	NO_x
230	12	0.30	0.91	1.48
4426	12	0.31	0.98	1.62
8820	12	0.31	1.21	1.72
13857	12	0.35	1.50	1.58

NOTES:

[1] Certification test procedure

[2] Slave canister procedure, GM reports that 1 g/mi CO should be added to CO levels due to variations in test procedures

REF. 11

TABLE 4.2 (Continued)

"In Service" Fuel Economy Summary
California Division Of Highways
Underfloor Converter Fleet

13 Oldsmobiles (No Air Pumps)

Average Fuel Economy (MPG)	10.6
Fuel Economy Range (MPG)	10.2 - 11.0

12 (AIR) Oldsmobiles

Average Fuel Economy (MPG)	11.0
Fuel Economy Range (MPG)	10.0 - 11.8

No comparable fleets of production vehicles available for comparison.

Seventy to eighty percent of the unburned HC and CO of a 1975 catalyst-equipped vehicle is given off during the first two minutes after cold start. Methods to reduce the amount of fuel used during choking will both lower emissions and increase fuel economy. The 1975 emissions-control systems will use reduced choking times and will employ provisions for using exhaust heat for early fuel evaporation. Systems that have promise of effecting even better control during start-up include electrical heating of a charge of fuel, electronically operated chokes, use of a small catalyst during start-up that will reach operating temperature in a short time, etc. Further reduction in emissions is possible by increasing the quantity of active material in the catalyst and in some cases, by increasing catalyst volume.

To reduce NO_x levels below the 1977 level of 2.0 g/mi while retaining control of HC and CO, increased amounts of EGR will be necessary. The resultant richer mixtures required to maintain flame speeds and driveability will lead to fuel economy penalties. The latter may be minimized by using greater spark advances, but this will, in turn, require extra control of HC.

Except for small, low-powered cars, where NO_x outputs are basically low due to the low flows required, it is doubtful whether a significant number of vehicles with conventional engines and oxidation catalysts would be able to reach levels of 0.41/3.4/1.5 g/mi without additional control measures or without excessive fuel economy penalties.

5. AIR/FUEL MIXTURE PREPARATION

5.1 Introduction

For emissions control to 1975 levels, considerable improvement in mixture preparation and delivery has been achieved. To reduce engine emissions and also to prevent an excessive burden on the oxidation catalyst, reductions of variations of A/F ratio from cylinder to cylinder and over the driving cycle have been necessary.

Further improvement in mixture preparation will be required to meet stricter standards. A closer A/F ratio control is essential for lower NO_x emissions because all known NO_x control methods result in poor driveability and fuel economy if the mixture is allowed to vary widely. NO_x catalyst technology specifically requires very high A/F ratio control which cannot be met with good presently used carburetors.

Another approach to minimize emissions and to maintain or improve economy does not involve the use of catalysts. In a warm engine, the optimum A/F ratio for minimizing all three pollutants is on the very lean side of stoichiometry; e.g., at A/F ratios larger than 18-20:1 as illustrated in Figure 5.1 where HC, CO, and NO_x emissions are plotted against A/F ratio. With current technology in mixture preparation and engine design, however, very lean mixtures rob the engine of horsepower output and increase fuel consumption, shown also in Figure 5.1. Engine and mixture-preparation technology are under development which will extend the range of adequate fuel economy and power output of lean mixtures as shown by the dotted lines in Figure 5.1. In this section, a discussion of improved mixture preparation methods will be presented which will be required for advanced emissions-control systems on conventional engines. Included will be advanced design carburetors, fuel injection and feedback control systems. Later sections of this report will deal with the emissions and fuel economy potential of lean engines and NO_x catalytic systems.

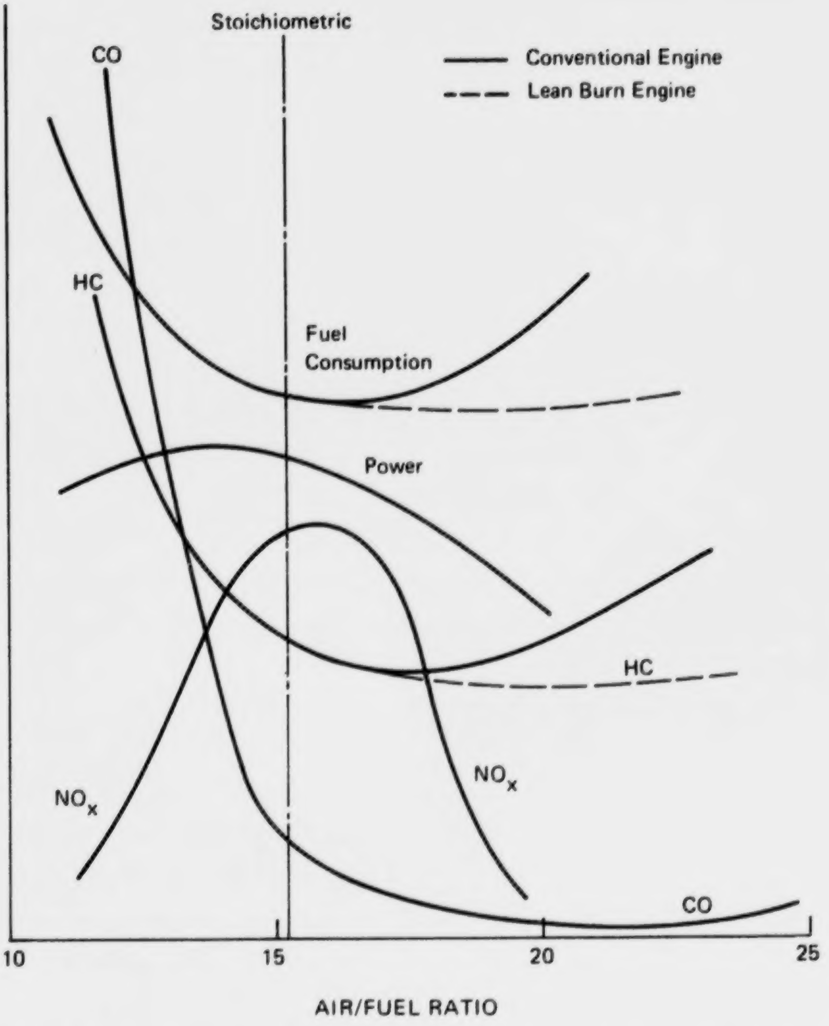

FIGURE 5.1 The Relationship of Typical Engine Emissions and Performance to Air/Fuel Ratio. The Vertical Scale is Linear and Shows Relative Rather than Absolute Values for Each Parameter.

5.2 Carburetors

a. Conventional carburetion -- The amount of fuel issuing from the jet situated in a Venturi of a carburetor increases at a faster rate than that corresponding to an increase in air intake. The mixture formed by a simple carburetor thus becomes richer as the engine aspirates more air and, consequently, a mixture which is correctly proportional for high air (full load) will be too lean at lower air flows (idle and part load). Figure 5.2 illustrates the A/F ratio control of such a simple carburetor as a function of Venturi vacuum (or the equivalent parameter engine rpm at part load).

An engine equipped with such a carburetor will run too rich at medium to full-load operation if excessive leaning out at idle is to be avoided, and for this reason such an engine would be highly polluting and poor in fuel consumption.

Modern carburetors achieve better A/F ratio control over the full speed/load range by using idling and full-load Venturis, idle speed and transition orifices to supply additional fuel at idle, acceleration pump, etc.

Figure 5.3 illustrates a cross section of a Weber multijet carburetor.[12]

A typical calibration curve which is conventionally used to provide for the mixture needs of an engine operating under all speed-load conditions is illustrated in Figure 5.4 for a single-barrel carburetor as used on the Vega 4-cylinder engine and with a carburetor used on Chevy 6's in the 1960's (dotted line).[13] The throttle is gradually opened from A(a) to D(d) and held wide open from D(d) to E(e) and F(f). As the engine slows down the D-E-F line the A/F ratio leans out because less air is being pulled through the carburetor. The engine comes to a lugging stall at point F.

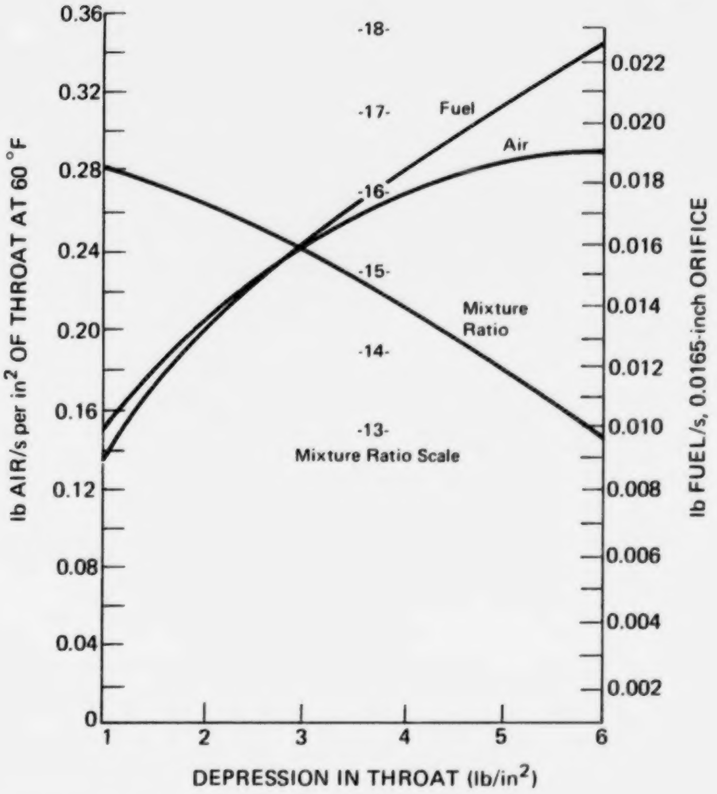
0.36
0.32
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0
lb AIR/s per in^2 OF THROAT AT 60 °F
-18-
-17-
-16-
-15-
-14-
-13-
Mixture Ratio Scale
Fuel
Air
Mixture Ratio
0.022
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
lb FUEL/s, 0.0165-inch ORIFICE
1
2
3
4
5
6
DEPRESSION IN THROAT (lb/in^2)

FIGURE 5.2

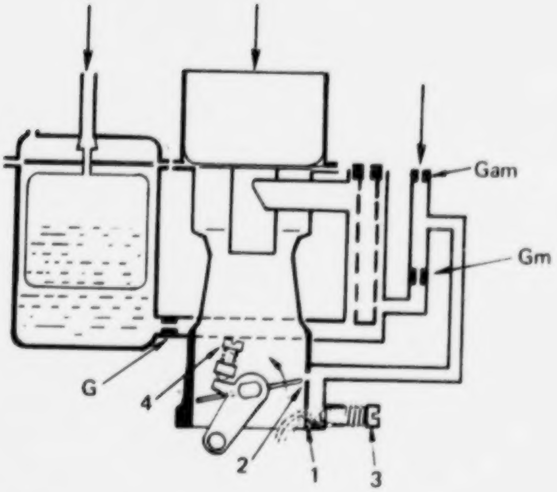

FIGURE 5.3 Idle Speed Circuit

Gam - Idle Speed Air Jet
Gm - Idle Speed Fuel Jet
G - Main Fuel Jet
1 - Idle Speed Mixture Orifice
2 - Transition or Progression Orifice
3 - Idle Mixture Adjusting Screw
4 - Throttle Setting or Idle Speed Adjusting Screw

Source: Reference 12

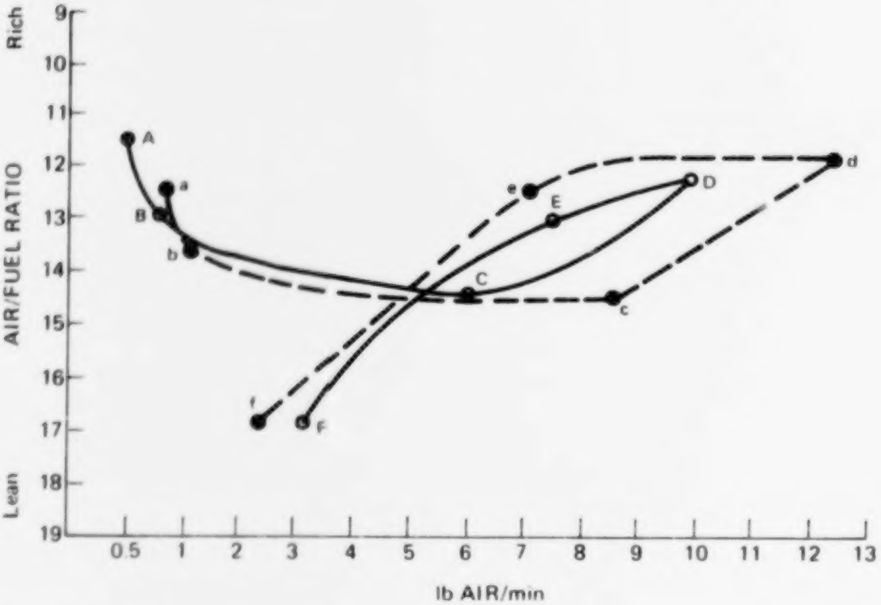

FIGURE 5.4

Source: Reference 13

Pre-emission-control carburetors were able to reproduce the A/F calibration curve within a band of ±5% to 10%; present carburetors have narrowed the band to ±3%. These figures are, however, deceptive because they do not reflect the dynamic A/F ratio changes which occur during acceleration, deceleration modes, changes in altitude, air and fuel temperatures, air humidity, etc., which all affect A/F ratio control.

A more serious problem with conventional carburetors is the variation in A/F ratio distribution from one cylinder to another cylinder. This problem arises from the fact that normal aspiration in a fixed Venturi carburetor results in relatively large fuel droplets which tend to segregate in the manifold. This segregation is more pronounced with cold engines, and under idle or low-load operation of the engine where the low air velocity through the Venturi results in large droplets which are difficult to distribute.

Variations as large as 20% in the cylinder-to-cylinder A/F ratio distribution have been reported for some European and American engines (see Figure 5.5).[14,15] The resulting emissions are high in HC and CO and can lead to premature catalyst failures. Improved carburetor manifold designs have reduced the A/F ratio spread to about 5%.

The cost of the more complex carburetors has been increasing. A simple single-barrel carburetor costs approximately $5 to $10; the more complex multibarrel carburetors, with altitude compensation and other ancillary controls, may cost as much as $40. The fuel economy and emissions control which can be realized with these carburetors are marginal when compared with new mixture preparation devices, and it is reasonable to assume that the conventional carburetor will be gradually phased out by other devices in the foreseeable future.

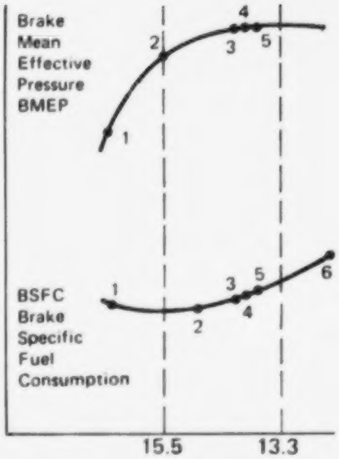

FIGURE 5.5 Air/Fuel Ratio Distribution in an 8-Cylinder Engine.

Source: References 14, 15

b. Variable Venturi carburetors and constant depression carburetors -- Variable Venturi and constant-depression carburetors overcome the problems of low air velocities which were described in the previous section by varying the area of the Venturi in accordance with the weight of air that is required per unit time by the engine. The Venturi can thus provide depressions and air velocities which are adequate to cause fuel to flow and be dispersed under most operating conditions of the engine. These carburetors also feature a variable area fuel orifice that varies with the changes in area of the Venturi in such a manner that the desired A/F ratio is provided at all times. Figure 5.6[16] shows an example of such a carburetor.

The piston valve can slide up and down in its guide and change the air passage or Venturi area. As the valve changes the area of the Venturi throat, it also moves the tapered metering pin in the fuel jet opening, and thus it provides a varying fuel jet orifice. The dash pot reduces the movement of the piston and prevents rapid upward movement when the throttle is operated rapidly.

The low pressure or partial vacuum at the throttle end of the Venturi throat causes air to flow through the piston vent until the pressures in the vacuum chamber and Venturi throat are equal. The lower side of the flex diaphragm has atmospheric pressure acting on it, and the force due to the pressure differences lifts the piston up or down.

Thus, for each air flow rate through the Venturi there is a corresponding position of the piston valve, and a particular value of the vacuum in the throat of the Venturi. The size of the fuel jet orifice and the taper of the metering pin are made so that the fuel flow with any given position of the piston valve is the desired flow.

Most carburetor companies are working on some version of the Variable Venturi (V.V.) carburetors. Most have chosen combination

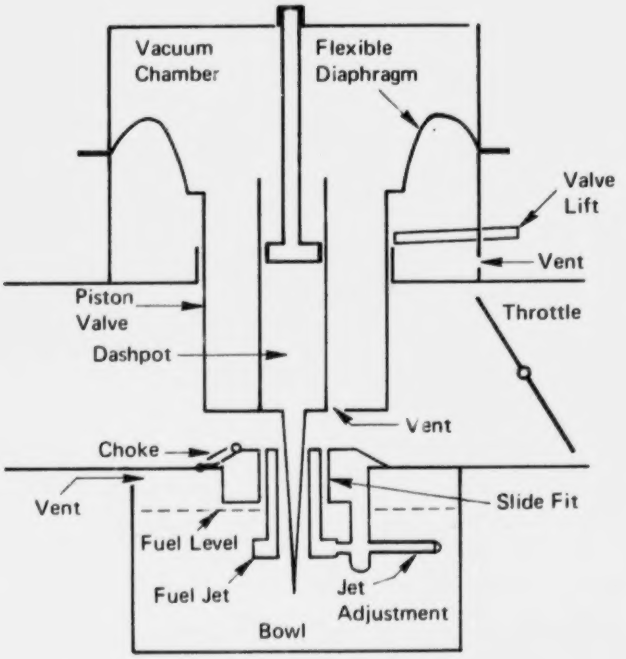
Vacuum Chamber
Flexible Diaphragm
Valve Lift
Vent
Piston Valve
Throttle
Dashpot
Vent
Choke
Vent
Slide Fit
Fuel Level
Fuel Jet
Jet Adjustment
Bowl

FIGURE 5.6

Source: Reference 16

carburetors with one barrel operating with a fixed Venturi while the other performs as a V.V. version. This version of carburetor appears to have the best chance of being interfaced with electronic controls as will be discussed later.

Table 5.1 summarizes some results which were achieved with a 1973 Dodge Monaco with a 1974 360 CID V-8 engine and the experimental Holley model 2880 Variable Venturi carburetor.[17]

TABLE 5.1

A/F ratio control ±3%

HC = 1.48 g/mi

CO = 10.28 g/mi

NO_x = 1.8 g/mi

Spark timing - 60° BTC

No air pump

10% EGR

Fuel Economy - 11 mpg

A fixed Venturi 4-barrel carburetor of similar design has higher HC and CO emissions (approx. HC - 2.5 g/mi, CO - 20 g/mi) and equivalent fuel economy. NO_x remains unchanged.

In spite of these improvements, the Variable Venturi carburetor will not achieve the A/F ratio control required for the three-way catalyst and simultaneous control of HC, CO, and NO_x.

c. Sonic carburetors -- The size of droplets produced by a carburetor varies approximately inversely with the velocity of air flowing through the Venturi. Figure 5.7 shows the relationship between air velocity and fuel droplet diameter entering the intake manifold.[18,19] The droplets which are achieved at sonic velocities (approximately 1000 ft/sec) and above are so small that little segregation occurs within the carburetor and intake manifold, and,

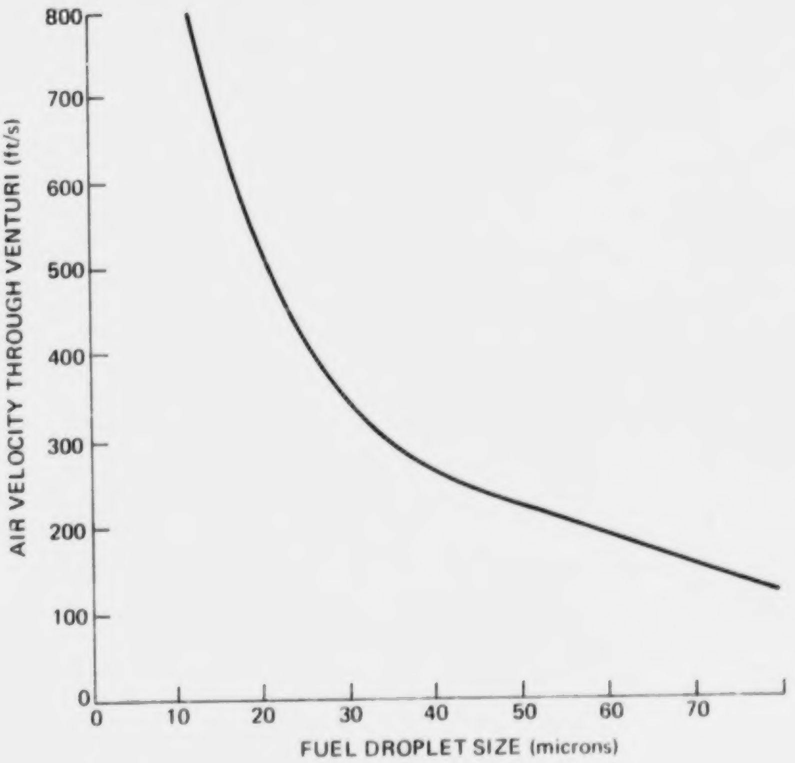

FIGURE 5.7

Source: References 18, 19

consequently, sonic carburetors have much lower cylinder-to-cylinder A/F ratio variations than conventional carburetors.

The Dresser carburetor is the best known sonic carburetor and considerable work is being performed throughout the industry to develop its potential.

The Dresser carburetor or "Dresserator" is a Variable Venturi carburetor with a mechanically actuated fuel distribution bar.[20] The principle is shown in Figure 5.8.[21]

The device shows promise of improving atomization, mixture quality, A/F distribution, and control. It achieves these improvements by:

- Designing the entrance/exit geometry to produce sonic flow at the carburetor throat which results in superior fuel atomization.
- Introducing fuel over a large surface area which is subjected to sonic air-flow levels.
- Passing the A/F mixture through a shock wave to atomize the fuel and improve mixing.
- Eliminating flow distortion caused by downstream throttle plates.
- Coupling the throttle with a linear fuel-control valve to achieve constant A/F control.
- Eliminating the choke, although some enrichment is necessary during start-up.

The mixture quality which can be achieved with sonic carburetors is compared with conventional production carburetors, EFI, stratified-charge engines (PROCO) and liquid propane (LPG) or liquid natural (LNG) cars in Figures 5.9 and 5.10 for various points in the induction system.[22]

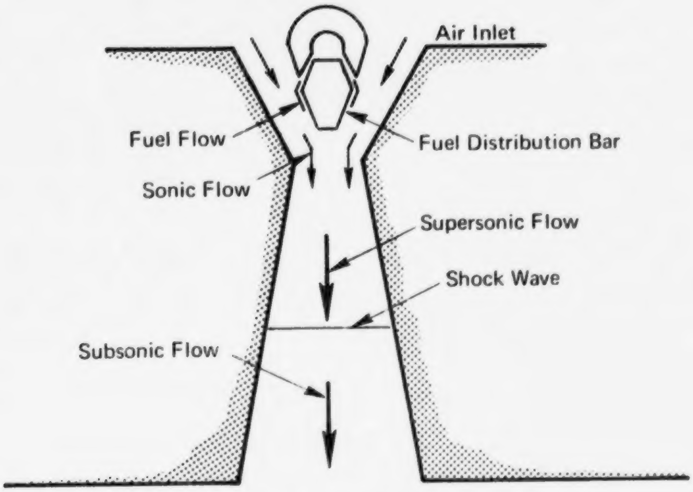
Air Inlet
Fuel Flow
Fuel Distribution Bar
Sonic Flow
Supersonic Flow
Shock Wave
Subsonic Flow

FIGURE 5.8 Sonic Carburetor Principle.

Source: Reference 21

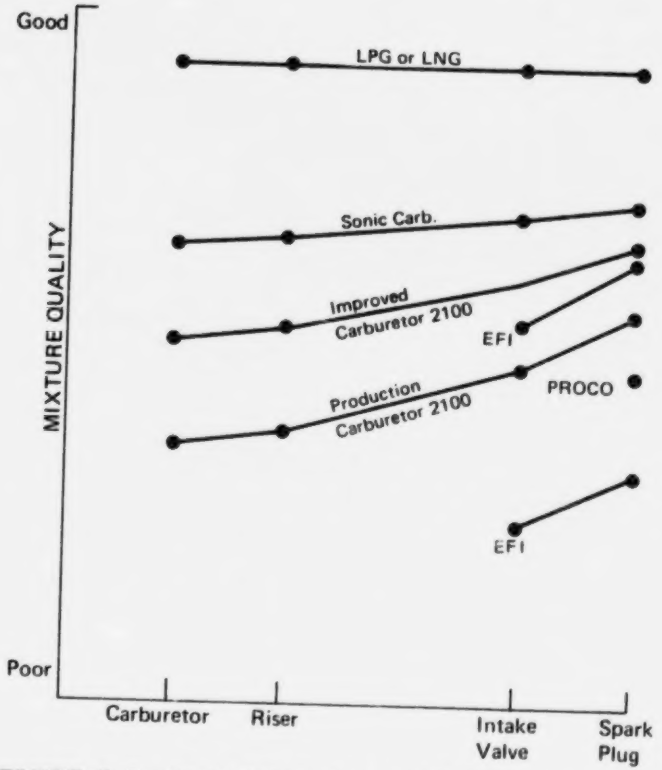

FIGURE 5.9 Ford Motor Company Estimate of Induction System Mixture Quality Trends Under Hot Operating Conditions.

Source: Reference 22

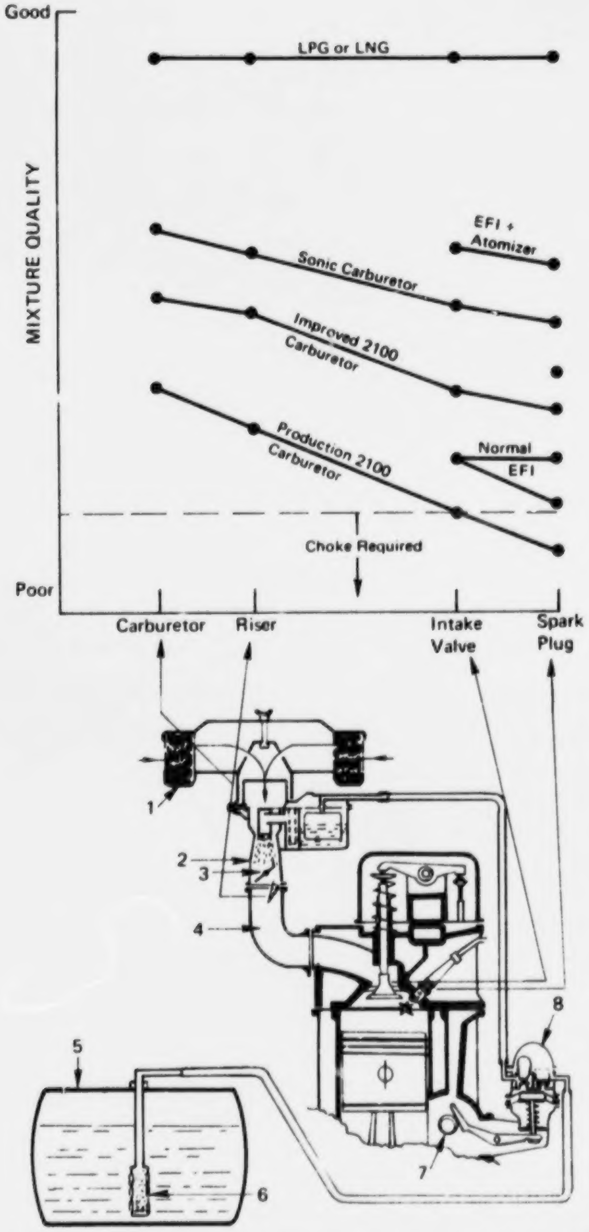

FIGURE 5.10 Ford Motor Company Estimate of Induction System Mixture Quality Trends Under Cold Start and Drive Conditions.

Source: Reference 22

With exception of LNG and LPG, sonic carburetion provides the most homogeneous mixtures and thus improved distribution.

Sonic carburetion is still in the development stage and a variety of problems remain to be resolved among them:

- Actuation forces under sonic conditions are high and lead to rapid component wear,
- Need for altitude and temperature compensation,
- Manufacturability and durability,
- Cold start where sonic velocities cannot be achieved.

d. Hot-spot carburetors -- As was shown in Figures 5.9 and 5.10, LNG and LPG produce better mixtures than gasoline because they evaporate more readily than gasoline in the operating temperature range of the engine. Similarly, cylinder-to-cylinder A/F ratio variation could be eliminated by vaporizing and mixing the gaseous gasoline with the incoming air. Several difficulties are associated with this approach are:

- The heat required to vaporize all fuel under full-load conditions is over 2KW and cannot be supplied by the automotive electric power.
- The fuel evaporator has to be designed to prevent simultaneous heating of the incoming air and associated volumetric efficiency losses.
- Vapor lock has to be prevented.

None of the fuel evaporation systems which are presently under evalutation has resolved these problems satisfactorily.

Most automobile manufacturers use hot spots or early fuel evaporation (EFE) devices to help during cold start. These are turned off as soon as the engine reaches operating temperature and therefore do not influence the cylinder-to-cylinder A/F ratio distribution of the warm engine.

The Ethyl Corporation, Shell Laboratories in England, and British Leyland[23,24,25] are experimenting with evaporative heaters which are kept in operation during the full operating range of the engine. The objective of these approaches is to improve the A/F ratio distribution to allow ultralean operation of the engine under all load conditions.

The Ethyl Corporation's hot-box manifold is shown in Figure 5.11.

The hot box is situated underneath the primary barrels of a Quadrajet carburetor and sunk into the exhaust manifold crossover. The fuel/air mixture of the primary barrel passes through the hot box under all driving conditions; the air/fuel mixture of the secondary barrel, on the other hand, bypasses the hot box under all conditions.

Since the air-flow velocities of the secondary barrel provide for good fuel distribution without evaporation, the resulting A/F distribution is better under all driving loads. The main flow of air is not heated by this system and, therefore, the volumetric efficiency is maintained. The cylinder-to-cylinder variation of this carburetor mounted on a 350 CID Plymouth engine is shown in Table 5.2.[23]

The A/F ratio spread with this carburetor is approximately 3% under idle and 1.6% at 30 mph. This is an improvement of a factor of 2 over a conventional carburetor. Further improvement are anticipated from a variable Venturi arrangement in the secondary barrel.

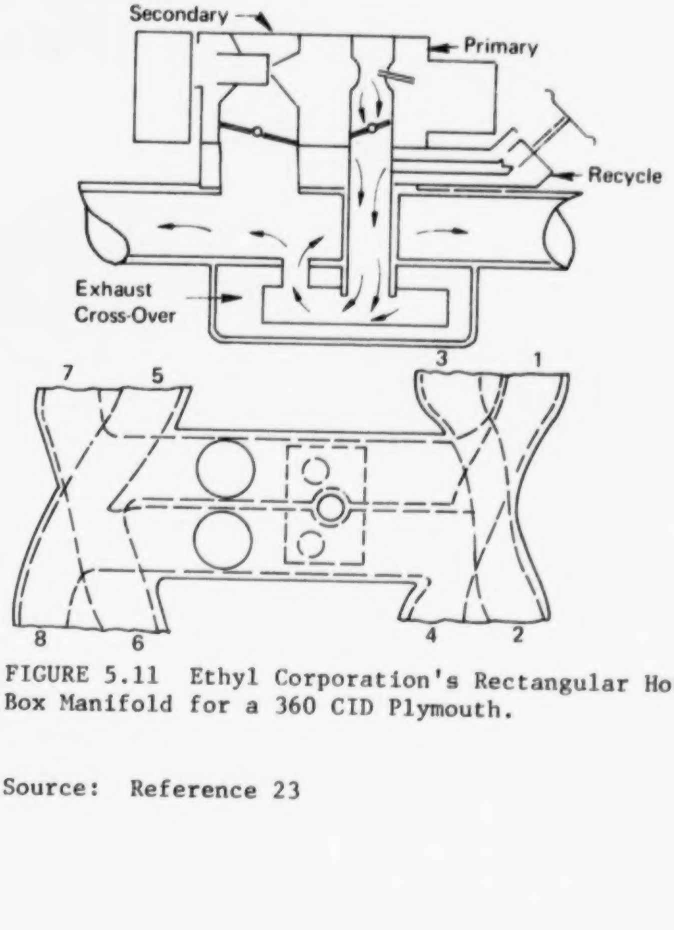
Secondary
Primary
Recycle
Exhaust
Cross-Over
7
5
3
1
8
6
4
2

FIGURE 5.11 Ethyl Corporation's Rectangular Hot Box Manifold for a 360 CID Plymouth.

Source: Reference 23

TABLE 5.2

Cylinder-To-Cylinder Distribution Spreads

	Cruise		Δ Distribution	
Speed	A/F[1]	F/A[2]	Δ A/F	Δ F/A
Idle	16.3	.061	0.50	.0020
15	17.5	.057	0.49	.0016
30	17.3	.058	0.28	.0009
50	16.6	.060	0.47	.0016

[1] A/F = air/fuel ratio

[2] F/A = fuel/air ratio

Typical emissions results for a modified* 1974 Dodge 4,500 lb 360 CID engine are (g/mi):

HC -- 1.33, can be improved to 1.1-1.2
CO -- 7.80, can be improved to 6-7
NO_x -- 2.76, can be improved to 2.3-2.5
Fuel economy -- 10.7, can be improved to 11.2 mpg

Base-line figures for the conventional Quadrajet carburetor are (g/mi):

HC -- 2.8
CO -- 26.0
NO_x -- 2.5-2.7
Fuel economy -- 11.0

The Shell Laboratories' (England) Vapipe approach is to use the exhaust heat to heat and evaporate all the fuel under all engine operating conditions.[24] Heat is transferred to the carburetor with heat pipes which are connected to the exhaust manifold (see Figure 5.12).

The results are similar to those achieved by Ethyl Corporation:

- The engine can be operated at very lean A/F ratios without losing driveability.
- The A/F cylinder-to-cylinder distribution is excellent (Table 5.3).

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*Equipment:
Carter Thermo-Quad Carburetor
Electric choke assist
Ethyl hot-box manifold
EGR -- control with Venturi and throttle position sensor
Timing 5° BTC

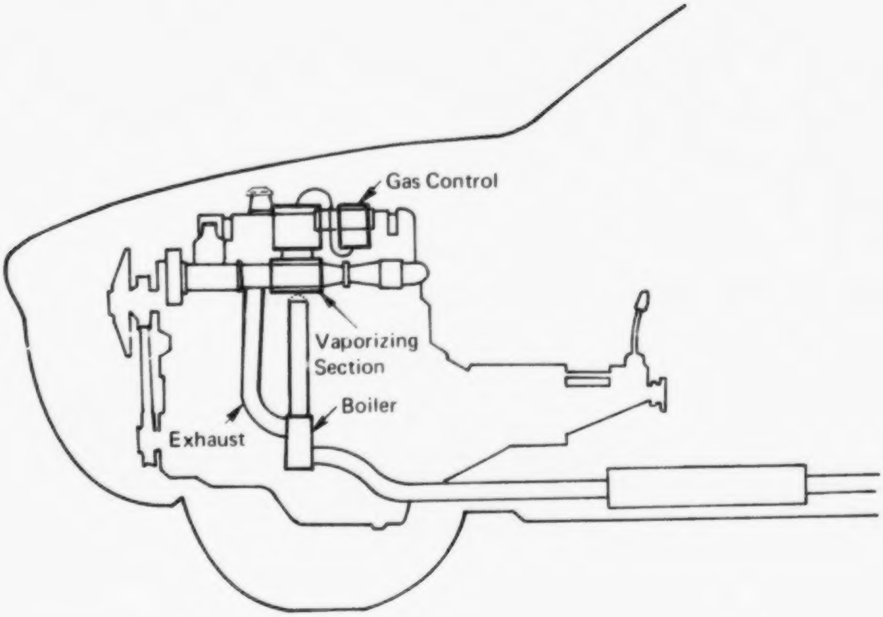

Gas Control
Vaporizing Section
Boiler
Exhaust

FIGURE 5.12 Location of Vapipe.

Source: Reference 24

TABLE 5.3

COMPARISON OF AIR-FUEL RATIO DISTRIBUTION
WITH AND WITHOUT VAPIPE - 1.8 LITRE (110 CU.IN.) CAR

Test Condition	Standard Car - Standard Setting				Vapipe Car - Standard Setting				Vapipe Car - Lean Setting			
	Overall Tailpipe	Cyl.1	Cyl. 2 & 3	Cyl.4	Overall Tailpipe	Cyl.1	Cyl. 2 & 3	Cyl.4	Overall Tailpipe	Cyl.1	Cyl. 2 & 3	Cyl.4
Idle	13.2	13.1	13.4	12.9	13.1	13.1	13.1	13.1	16.5	16.4	16.5	16.4
Road Load 30 mph 48 km/h	14.2	15.4	13.5	14.2	13.4	13.5	13.4	13.4	16.3	16.6	16.3	16.5
Road Load 50 mph 80 km/h	15.4	15.8	15.2	15.6	15.8	15.8	15.8	15.8	17.9	17.7	18.0	17.9
Road Load 70 mph 112 km/h	15.0	15.3	14.9	16.1	14.8	14.8	14.7	14.7	16.6	16.7	16.6	16.6
Full Throttle 30 mph 48 km/h	14.3	14.7	13.5	15.3	13.6	13.7	13.6	13.9	17.1	17.4	17.2	17.5
Full Throttle 50 mph 80 km/h	13.6	13.3	12.9	14.8	13.5	13.8	13.5	13.6	16.6	17.0	16.6	16.7

- The emissions of all three pollutants are lowered.
- Fuel economy is improved over that of the same engine with a conventional carburetor.

e. Carburetor with ultrasonic fuel dispersion -- Recently several carburetor-like devices have been proposed which use ultrasonic energy to achieve good fuel dispersion and cylinder-to-cylinder mixture distribution. One version is being developed by Autotronics. Another version, which has been proposed by Dr. A. K. Thatcher and Dr. Ed McCarter, Florida Technical University,[26] uses a magnetostrictive transducer at frequencies of 20,000 to 40,000 Hz to break up the fuel stream into very small droplets. The device is shown in Figure 5.13. Fuel injectors spray fuel onto the surface of the horn of a magnetostrictive transducer where the fuel is atomized into very small droplets which are mixed with the flowing air. The device was evaluated on a Plymouth Duster with a 225 CID slant six engine and is summarized in Table 5.4.

TABLE 5.4

Duster with Ultrasonic Device (g/mi)	Duster with Std. Carburetor (base-line) (g/mi)
HC - 0.44	4.9
CO - 0.88	6.6
NO_x - 1.0 ± 30%	3.0 to 8.0
MPG - 22	18

The base-line HC and NO_x emissions seem overstated; however, the improvements in emissions levels with this system are believable. The large difference in fuel economy cannot be justified by what is

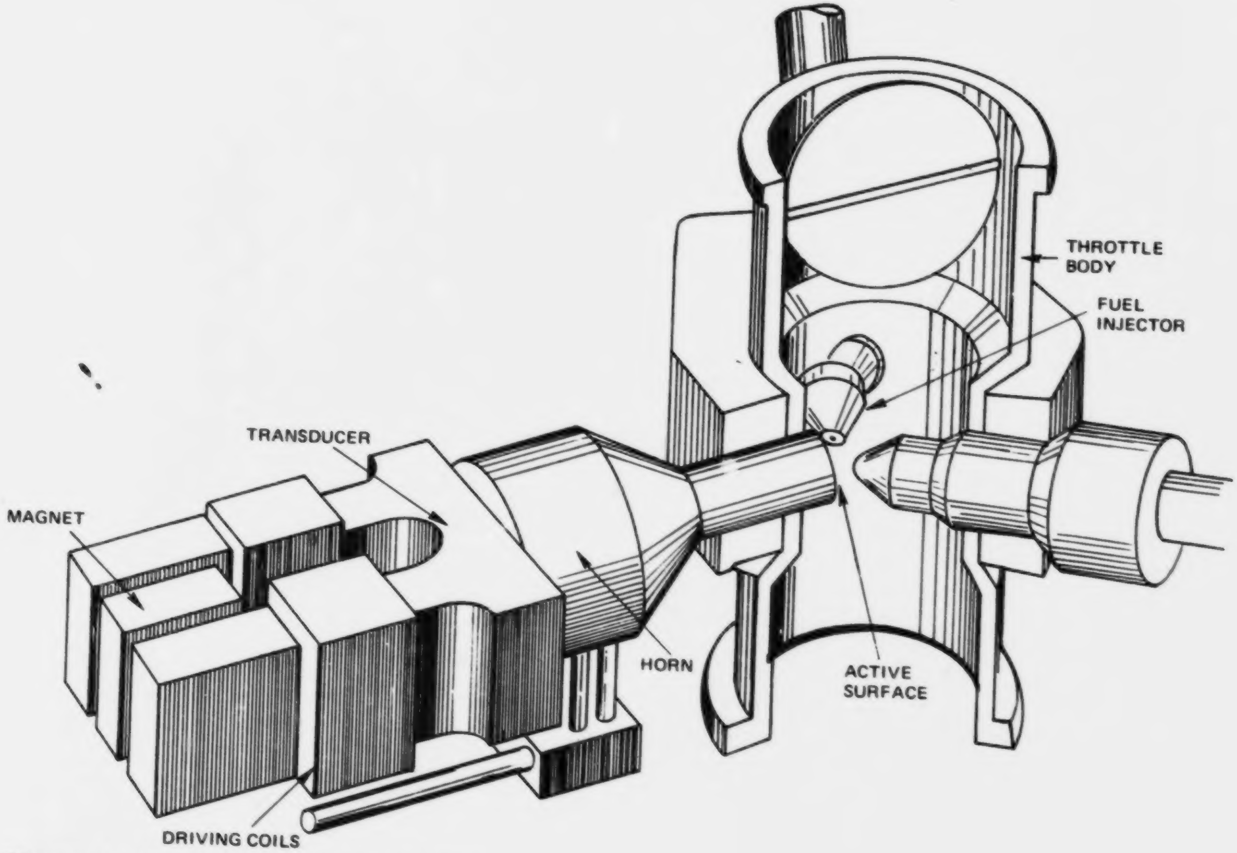

THROTTLE BODY
FUEL INJECTOR
TRANSDUCER
MAGNET
HORN
ACTIVE SURFACE
DRIVING COILS

FIGURE 5.13 Ultrasonic Carburetor.

Reprinted courtesy of Popular Science, 1973, Popular Science Publishing Company

Source: Reference 26

known about the device alone. The drawbacks of the system, as presently implemented, are high power consumption, noise, complexity, and thus, high cost. Therefore, it seems that the objective of better fuel dispersion may be accomplish more easily with a sonic or hot-spot carburetor or fuel injection.

5.3 Fuel Injection Systems

a. Electronic fuel injection - speed and density systems -- The oldest electronic fuel injection system (invented by the Bendix Corporation approximately 15 years ago and perfected and manufactured by Robert Bosch, Germany) measures air density and engine speed to derive the air quantity drawn in by the engine and to inject the appropriate amount of fuel.

Robert Bosch started production of this system in 1967 and has presently 1.5 million of the D-jetronic EFI types in the field installed on 40 different 4-, 6-, and 8-cylinder engines. The principle of the system is illustrated in Figure 5.14.[27,28]

The air quantity drawn in by the engine is determined by measuring the engine rpm and electronically multiplying this figure by the engine displacement constant. A manifold vacuum pressure transducer and an ambient air temperature sensor convert the air volume to standard temperature and pressure (STP). The electronic control logic processes these signals and injects the appropriate amount of fuel into the intake manifold through fuel injectors which are positioned on top of the cylinder heads. Fuel is fed to these injectors through a well-regulated, pressurized fuel rail.

The D-jetronic system is a pulsed injection system where the quantity of fuel is modulated by changing the length of the injection pulse. The D-jetronic system sells to the original equipment market (OEM) in Europe for approximately $120 for a 4-cylinder version.[29] For this reason, it has found only limited application in spite

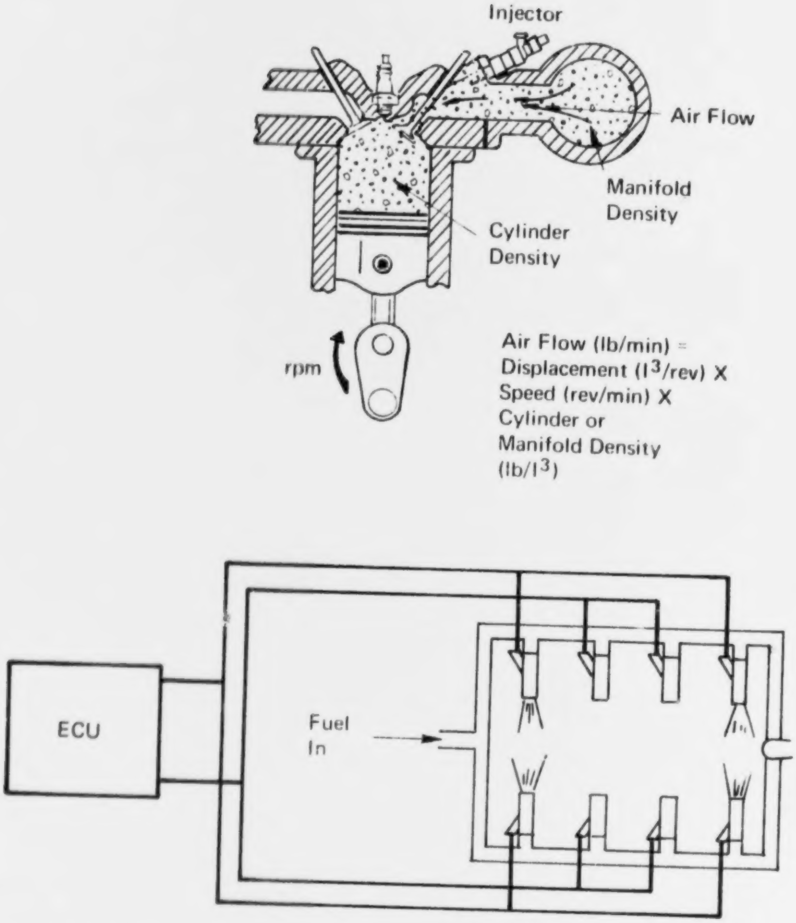

Injector
Air Flow
Manifold Density
Cylinder Density
rpm
Air Flow (lb/min) = Displacement (l^3/rev) X Speed (rev/min) X Cylinder or Manifold Density (lb/l^3)
ECU
Fuel In

FIGURE 5.14

Source: References 27, 28

of the fact that it has been offered in Europe for over seven years. The Bendix Corporation in the United States has developed a similar speed density system but has failed to find wide acceptance again, mainly due to the high cost of the system.[27]

There is considerable controversy about the benefits of electronic speed density fuel injection systems:

- It is well established that the maximum power output for a given engine can be improved; for example, with electronic fuel injection (EFI), a 2.8 liter Daimler Benz gasoline engine delivers 185 hp at wideopen throttle (WOT) and only 150 hp with a carburetor.[30] This advantage is due to the better volumetric efficiency and full power enrichment with EFI. (The EFI manifold has fewer obstructions for the inrushing air.) This advantage is mainly realized at full throttle, particularly with high speed European engines - most current U.S. cars rarely operate at full load and would not benefit from EFI.

- Electronic fuel injection can offer better cylinder-to-cylinder A/F ratio distribution for poorly designed engine manifolds and engine types which have difficult induction problems. An example is the air cooled opposed piston engine used by Volkswagen.[14] This engine has long intake manifolds and a cylinder firing sequence which makes it difficult for some cylinders to get the correct charge. Traditionally, this engine was carbureted rich in order to assure that all cylinders had adequate mixtures. The consequences were high emissions. Electronic fuel injection solved the problem by supplying each cylinder with the appropriate amount of fuel. Electronic fuel injection, in itself, does not have any advantage over a well carbureted engine. For example:

Saab 2 Liter Engine 3,000 lb. Automobile[31]
(Raw Engine Emissions)

	HC	CO	NO_x	MPG
D-jetronic (dual catalyst)	1.18	40.9	2.19	16
Carburetor (dual catalyst)	1.9	40.7	2.4	17.7
Close loop K-jetronic (3-way catalyst)	0.9	8.14	2.2	19.3

- Electronic fuel injection improves cold-start performance, again, particularly for European engines with simple carburetors and choke systems. U.S. cars do not benefit from this feature.
- Some European manufacturers have opted to use EFI rather than to design an advanced carburetor because it was cheaper to do so.

In summary, D-jetronic EFI can offer some advantages in A/F ratio distribution for a few engines with difficult manifold and firing sequence problems. It improves cold start and power output at WOT. It does not offer fuel economy and emission advantages over well carbureted engines.

b. Electronic fuel injection - air mass system (L-jetronic)-- In 1972 Robert Bosch produced the L-jetronic system, a second generation EFI, which monitors the quantity of air drawn in by the engine directly with an air mass sensor as shown in Figure 5.15. This system has been described in several publications.[32-34] The air mass is measured by a flap situated in the main air stream. The force of the flowing air on the flap is balanced against the force of a return spring. To eliminate rapid pulsation, the device incorporates an air chamber and another flap which acts as a dash pot damper (stabilizer volume). A butterfly valve in the air flow measuring flap absorbs backfiring pulses. The flap angle is converted into voltage by the potentiometer which is attached to the axis of the flaps. This device eliminates the pressure and temperature

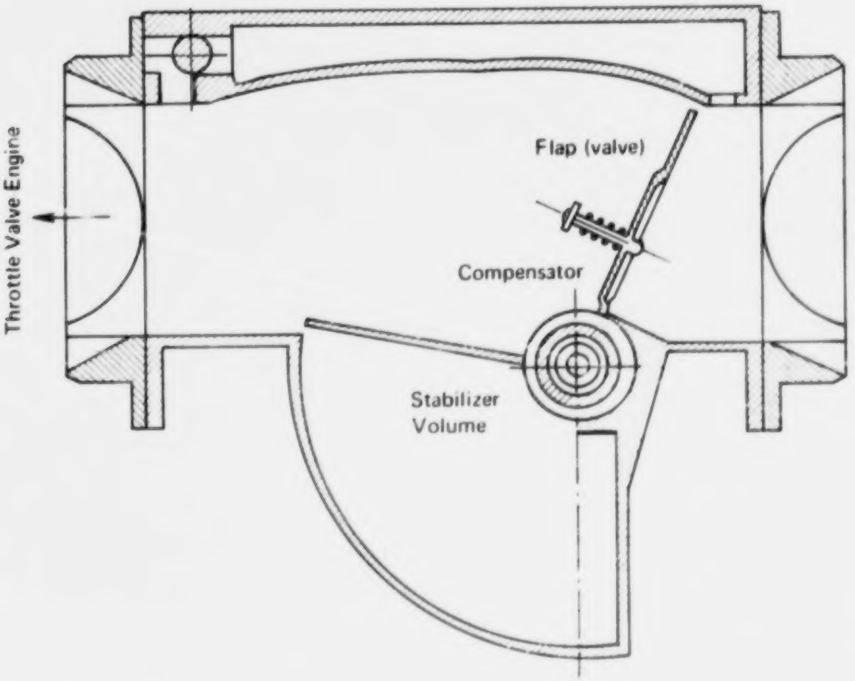

Throttle Valve Engine
Flap (valve)
Compensator
Stabilizer
Volume

FIGURE 5.15

Source: References 32, 33, 34

sensors of the D-jetronic system and simplifies the electronic circuit.

The rest of the L-jetronic system is similar to the D-jetronic system. It has a pressure regulated fuel rail, port injection, an additional injector for cold start, etc. The L-jetronic system, however, offers the following improvements:

- Improved start-up which leans out the engine faster.
- Deceleration control.
- Simultaneous injection of all injectors (rather than sequential) which allows the injection pulse length to increase and to reduce the injection time error. For example, at full load, the injection pulse is 8 msec with the L-jetronic and 4 msec with the D-jetronic EFI. Since the pulse rise time is 1.6 msec, the errors introduced at a 4-msec pulse width are considerable.

The L-jetronic EFI is more rugged and measures air more accurately. For example, the air-mass meter is independent of barometric and back pressure changes which throw off the calibration of the D-jetronic system, and it monitors air flow independent of EGR.

The L-jetronic system is approximately 10% cheaper than the D-jetronic system, viz., approximately $110 for a 4-cylinder European engine versus approximately $120 for the equivalent D-jetronic system. Because of these advantages, most users of D-jetronic EFI, particularly Volkswagen, will switch in 1975 to L-jetronic EFI.

The raw emissions of the L-jetronic system are lower than those achieved with D-jetronic EFI; 1975 Federal standards can be met comfortably. For example, a 1.6 liter air-cooled Volkswagen engine measured:[35]

HC - 1.16 g/mi
CO - 7.1 g/mi
NO_x - 1.22 g/mi

The L-jetronic system does not seem to offer significant fuel economy advantages. Volkswagen reports,[35] for example 18.3 miles per gallon in 1974 vs. 17.8 miles per gallon in 1975 for their Type 2 air cooled engine. Other models show slight increases in 1975.

In summary, the L-jetronic system reduces emissions when compared to the D-jetronic system. These improvements are due to better air measuring inputs, improvements in the start-up, deceleration controls, and injection timing. The L-jetronic system is capable of meeting the 1975 federal standard but cannot meet 1975 California standards without oxidation catalysts or thermal reactors. Fuel economy remains equivalent to D-jetronic or well carbureted engines.

c. Mechanical fuel injection (K-jetronic system) -- The K-jetronic system[36,37] uses the intake air volume as the controlling variable to determine the A/F ratio and to eliminate the need for electromechanical conversion. Figure 5.16 shows the schematic of the system.

The floating flap air-sensor plate is mounted on a lever having a balanced weight attached to the short end. The flow rate of intake airlifts the plate until an equilibrium is reached between air flow and hydraulic counter pressure which acts on the lever through a controlled piston. In this balanced position, the plunger maintains a certain position in the fuel distributor, thus opening small metering slits, one for each engine cylinder. The fuel supplied by a pressurized fuel rail system passes through the slit openings to the injection valves. The correct amount of fuel is provided by the slit openings, than in the injection valve as in

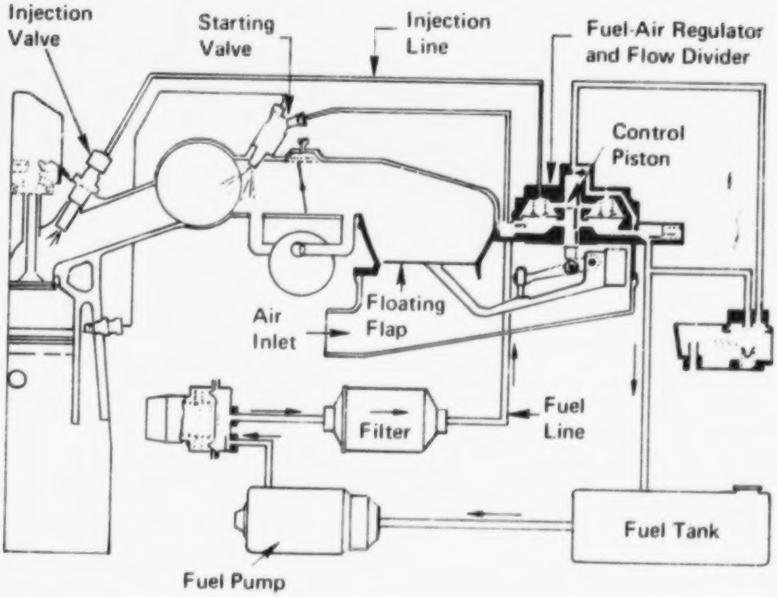

Injection Valve
Starting Valve
Injection Line
Fuel-Air Regulator and Flow Divider
Control Piston
Floating Flap
Air Inlet
Filter
Fuel Line
Fuel Tank
Fuel Pump

FIGURE 5.16

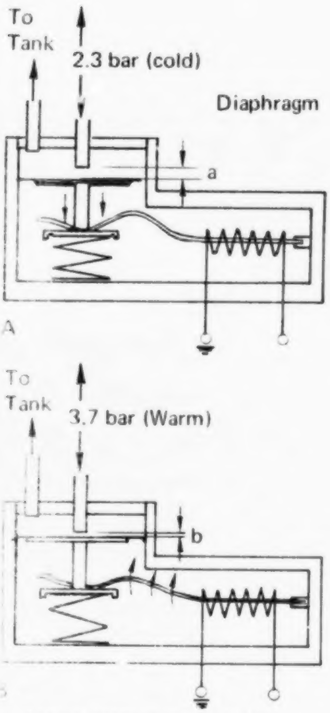
Source: References 36, 37

electronic fuel injection.

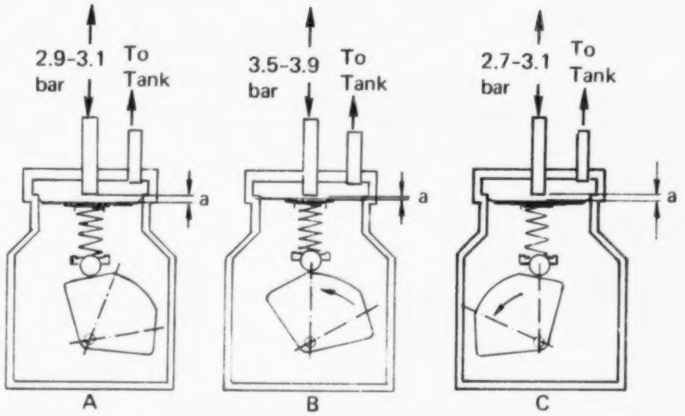
Hydraulic counter pressure acts on the top of the control piston to influence the fuel quantity needed by the various operating conditions of the engine. By exerting more force on the top, the plunger travels less, and less fuel flows to the injection valve. The opposite is true when the pressure is released. The control pressure is varied by control-pressure regulators, one regulating according to engine and outside temperature and the other according to accelerator pedal position. The controlled pressure regulator for temperature compensation maintains the correct A/F ratio by enriching the mixture during engine warm-up. As the engine reaches its normal running temperature, it leans out the mixture. This control-pressure regulator contains a bimetal spring which acts on a spring-loaded diaphragm (see Figure 5.17). For example when the engine is cold, the diaphragm keeps the inlet open to maintain a minimum pressure on the plunger of approximately 2.3 atm. As the heating coil of the bimetal spring heats up, it permits the diaphragm to close off the inlet opening, thus increasing the control pressure and leaning out the mixture.

The control-pressure regulator for throttle vavle position compensation is mounted on the throttle valve shift (see Figure 5.17). According to accelerator movement, the control pressure on top of the plunger is again changed to provide the correct A/F ratio. When the throttle is at idle, the control pressure is maintained at 3 atm. at mid-range throttle opening, 3.7; and at wide open throttle, 2.9; thus increasing fuel delivery as the throttle is depressed.

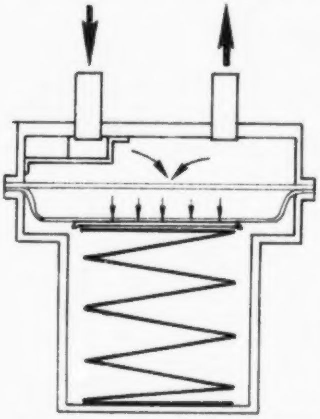
The K-jetronic system has a starting valve which provides additional fuel during start-up conditions, and has a number of significant advantages over both electronic fuel injection systems:


To Tank
2.3 bar (cold)
Diaphragm
a
A
To Tank
3.7 bar (Warm)
b
B

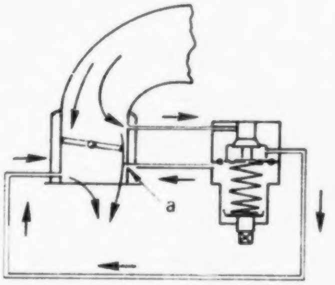
Control pressure regulator for warm-running compensation. A–cold position; B–warm position.


2.9-3.1 bar
To Tank
a
A
3.5-3.9 bar
To Tank
a
B
2.7-3.1 bar
To Tank
a
C

8. Control pressure regulator for throttle valve position compensation. A–idle position; B–midrange position; C–full-throttle position.



9. Fuel accumulator prevents vapor locking of the system.



10. Auxiliary air device assures good air-fuel ratio during deceleration.

FIGURE 5.17

Source: References 36, 37

- It is a simpler system and is understood by mechanics.
- It is lower in cost. The OEM cost for the system in small quantities is approximately $100 and is likely to be lowered as the volume production commences.
- The K-jetronic system is slightly better than the L-jetronic system in controlling emissions and improving fuel economy because it minimizes time lags associated with sensor signals and fuel-injection pulses.
- The K-jetronic system is capable of meeting the 1975 federal standards, but it cannot meet the 1975 California standards without a catalyst.
- In summary: The K-jetronic system provides the same advantages over carburetors as the other two electronic fuel-injection systems; namely, higher power output under wide open throttle conditions, less air induction problems and better cold start.
- The fuel economy is approximately the same as with the L-jetronic system, although Audi, Volvo, and Saab claim some minor advantages. Volvo claimed that the fuel economy of their two-liter, carbureted engine increased from 17 mpg to 19 mpg for the same engine with a K-jetronic fuel-injection system.[38] Saab,[39] on the other hand, showed an example during the Washington presentations of a carbureted engine with better fuel economy than one with K-jetronic injection.
- This difference in opinion illustrates the danger of extrapolating the emission and fuel economy results achieved with one type of intake-manifold-engine combination as compared to another even if the same carburetor or fuel-injection system is used in both.

- The emissions from K-jetronic injection are equivalent to those of the L-jetronic system.

5.4 Feedback Systems

The A/F ratio of an operating engine is influenced by the temperature of the air, temperature of the fuel, the humidity of the air, the chemistry of the fuel which affects density surface tension and viscosity, the absolute pressure of the air, the back pressure of the engine and the shifts in calibration of fuel metering rods, orifices, etc. Of all these variables, only a few are monitored with present fuel-metering devices:

- The advanced carburetor will have altitude compensation but has no sensors for air temperature, humidity, etc.
- The electronic and mechanical fuel-injection systems will also incorporate altitude compensation and air temperature measurements but do not monitor variables such as humidity, fuel viscosity, etc.

For these reasons, open-loop fuel metering cannot be correct under all conditions of vehicle operation. Only a closed-loop system which monitors either the composition of the exhaust gases or some engine output parameter, such as horsepower output, can maintain the A/F ratio within correct limits by constantly supplying corrective signals to the primary F/A metering device.

Two main approaches are being pursued at the present time:

- Systems based on the exhaust-gas composition, specifically, systems monitoring the oxygen content of the exhaust system;
- Systems based on engine output parameters, particularly horsepower output.

a. Feedback systems based on the O_2 - exhaust gas sensor and EFI, mechanical (continuous) fuel injection or electronic carburetors -- In 1971, Robert Bosch proposed a new exhaust-gas composition sensor which provides a strong variable voltage signal around the stoichiometric composition of the A/F mixture.[40] The sensor output was used to close the feedback loop with the L-jetronic electronic control unit and to correct the fuel injection pulses and maintain the A/F ratio at exact stoichiometric composition. The control achieved with this feedback was typically an order of magnitude better than that achieved with advance carburetors or approximately ±0.3% vs the ±3% achieved with the best carburetor system.

The heart of this control system is the oxygen sensor. Such a sensor is shown in Figure 5.18. It consists of a doped ZrO_2 tube with phatinum electrode on each side. One side of the sensor is exposed to the exhaust manifold gases, the other to the atmosphere. The sensor operates as an electrochemical oxygen concentration cell with ZrO_2 solid electrolyte. The platinum electrode acts as a reaction site for the reaction:

$$CO \quad + \quad O \quad CO_2 \text{ and}$$

$$HC \quad + \quad O \quad H_2O + CO_2 \, ,$$

and the sensor output is determined by the oxygen partial pressure of these reactions or the concentration of oxygen on the surface of the senor rather that the "free" oxygen concentration in the exhaust stream.

As the mixture goes from rich to lean, the partial pressure of oxygen on the surface will change by a factor of 10^{12} or more and, according to the Nernst equation, a step-like voltage change of almost one volt will appear across the electrodes of the sensor as

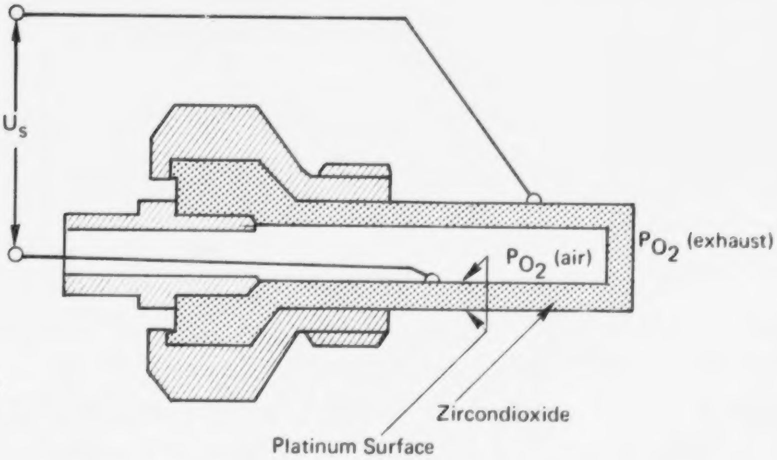

U$_s$
P_{O_2} (exhaust)
P_{O_2} (air)
Zircondioxide
Platinum Surface

FIGURE 5.18

Source: Reference 40

shown in Figure 5.19. A signal will always occur at stoichiometric exhaust gas compositions regardless of temperature or exhaust gas flow rate. The rise time of the signal is very rapid (milliseconds). The sensor has to be brought to at least 400°C before a useful signal appears and the output is temperature dependent as in Figure 5.20.[41] By choosing the control point at 500 mV or below, the temperature sensitivity can be eliminated because temperature changes occur mainly at the rich end of the output.

The problems which plagued the oxygen sensor a year ago thermal cracking, aging, and seal leaks, have been virtually eliminated, and Bosch in Germany and UOP in the U.S. claim to have sensors which can be guaranteed for 12,000 miles or more. The evidence submitted to support these claims was convincing.

The oxygen sensor feedback loop can be used in conjunction with the L-jetronic EFI, the K-jetronic mechanical injection system or electronic carburetors. The cost of feedback-control systems may decrease rapidly because they may eliminate many presently used ancillary control such as fast chokes, altitude compensation, air pumps, EGR, etc. The feedback control is very exciting new technology with great potential to achieve low emissions with low fuel consumption and control system cost.

b. Feedback system based on engine output sensors -- Dr. P. Schweitzer[42] has proposed to use an engine feedback signal to vary the mixture ratio of the engine under all driving conditions. The principle of the control or "Optimizer" system is illustrated in Figure 5.21.

In this version of the control system, the intake manifold system is provided with an auxiliary air intake passage. A dither plate continuously oscillates to change the air intake within narrow limits. As the mixture composition changes, the engine speed fluctuates within narrow, but well-defined limits. These variations

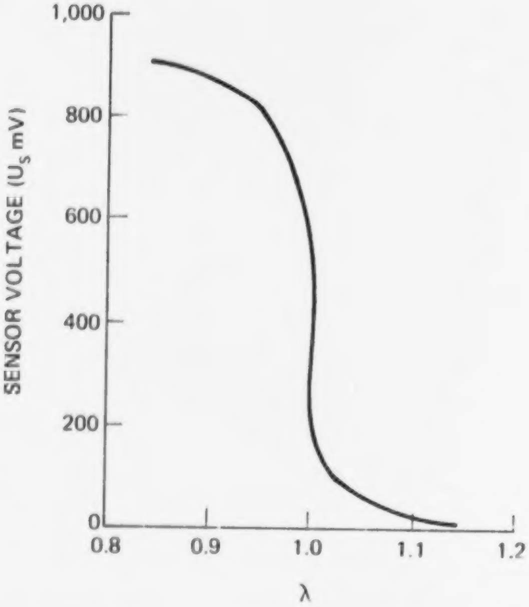


FIGURE 5.19 Sensor Characteristic.

Source: Reference 40

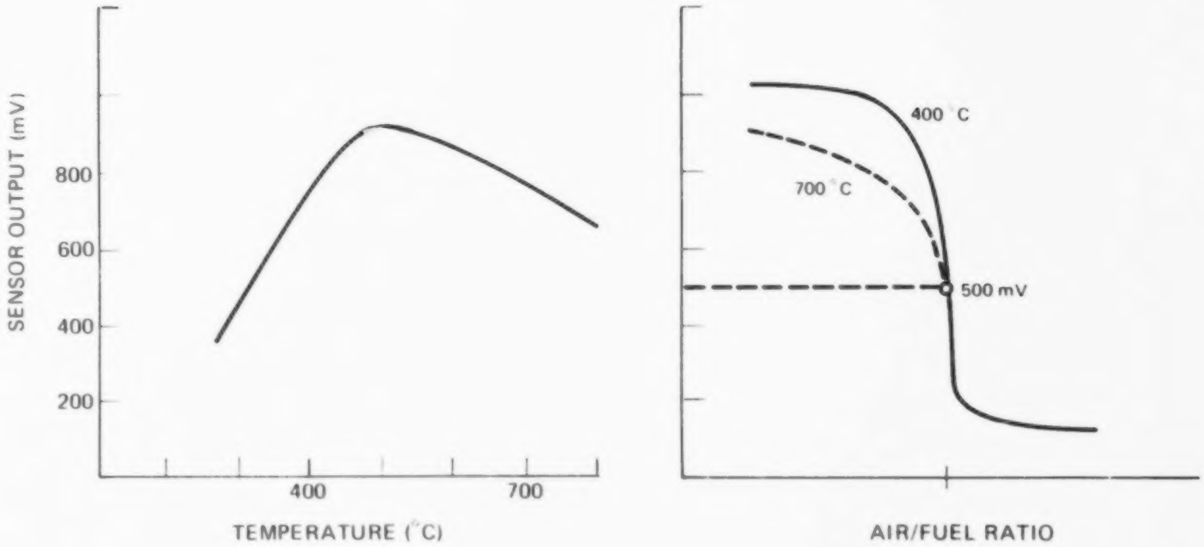


FIGURE 5.20

Source: Reference 41

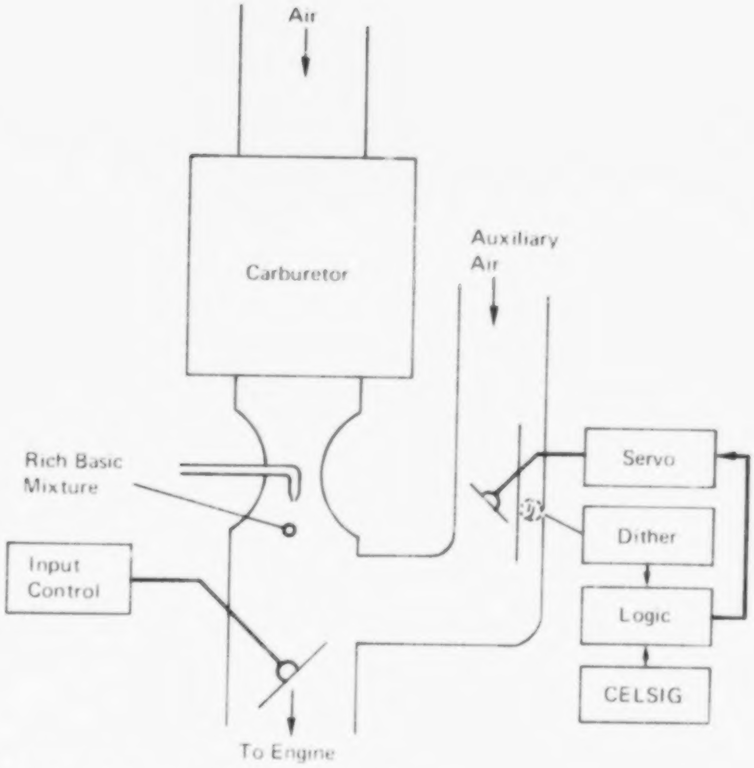

Air
Carburetor
Auxiliary Air
Rich Basic Mixture
Servo
Dither
Input Control
Logic
CELSIG
To Engine

FIGURE 5.21 Optimizer Control.

Source: Reference 42

in engine speed are monitored by a deceleration/acceleration sensor (the Celsig, the derivative of rpm information) and fed into the control logic. The control logic adjusts the main air intake to the engine in such a way that the change maximizes engine rpm. In this fashion, this control optimizes horsepower output of the engine under any driving condition and thus minimizes fuel consumption.

Dr. Schweitzer has made preliminary calculations of the system and claims lower emissions with improved fuel economy, but the system has not been tested on a car.

The optimizer control is probably useful for minimizing fuel consumption irrespective of engine emissions. Used in conjunction with a normally tuned carburetor, operating around stoichiometry, the emissions would probably be high because the optimizer control would tend to operate at the maximum power point which occurs at the rich side of stoichiometric.

The optimizer control may have more merit in conjunction with advanced carburetor or fuel-injection systems which maximize the power output on the lean side of stoichiometric. In this case, good fuel economy may be coupled with low hydrocarbon and carbon monoxide emissions. An example would be a combination of optimizer control with a sonic or hot-spot carburetor. It seems, however, mutually exclusive to optimize fuel economy and minimize NO_x with this method. Therefore, the usefulness of this feedback control will be small to achieve NO_x emissions below 2 g/mi.

6. LEAN BURN SYSTEMS

Maximum rates of NO_x formation occur at F/A equivalence ratios about 0.9 (fuel lean), Figure 5.1. Significant reduction in NO_x can be obtained by operating much leaner than this. Further, at lean mixtures, excess oxygen available provides for complete combustion of CO and HC and potentially low levels of these pollutants in the exhaust gas stream. Advantages in fuel economy can be realized by running lean, as long as means are taken to ensure complete combustion of the charge. At very lean A/F, as shown in Figure 5.1, HC levels start to increase as the quench zones become thicker and misfire is approached. Further, systems that use lean mixtures are generally limited by an exhaust temperature which can lead to high HC emissions. Retarding timing and reducing the compression ratio to achieve higher exhaust temperature and lower HC emissions leads to fuel economy penalties.

Conventional carburetors and induction systems are not adequate to maintain reliable operation at mixture ratios of 17:1 and leaner. It is especially important for lean operation to have a homogeneous mixture delivered to each cylinder at the same A/F ratio. Techniques to achieve such mixtures have been described in Section 5; namely, the Ethyl system, Shell Vapipe and Dresser carburetor.

Results from the Ethyl system, featuring a hot-box manifold, were presented on pages 33,36 and 37. When this system was modified to include an exhaust lean thermal reactor, with overall system A/F ratio 17:1, emission levels in Table 6.1 were achieved.

Table 6.1[43]

1974 Dodge, 360 CID, 4500 lb (Ethyl tests)

	With reactor
HC	0.55
CO	5.0
NO_x	1.40

Fuel economy, as measured on a cold-start 1972 test procedure, was 10% to 15% better than that of the base vehicle.

The Shell Vapipe system is designed for very lean operation with homogeneity achieved by fuel vaporization. Data have been obtained on a 1.8 liter Morris Marina of 2,500 lb inertia weight with manual transmission. This vehicle is made for the European market so has no EGR, and very little in the way of emissions controls except for the Vapipe. Results of the average of 6 tests on the 1975 FTP are[44]

HC	4.9 g/mi
CO	5.9 g/mi
NO_x	1.5 g/mi
MPG	22.6 MPG
A/F	16.5 to 1

Improvement in fuel economy has been achieved out to A/F ratio of 20:1 although at these very lean ratios, two spark plugs are necessary, with as much as 80^o advance. A problem that must be overcome with this system is the time required to bring the heat pipe into operation (2 minutes).

The most promising system for obtaining the advantages of lean operation through improved carburetion appears at present to be the Dresserator. The Dresserator carburetor is a variable-throat, supersonic nozzle, operating choked for manifold vacuum of less than 3 inches of mercury. Cold start is possible at A/F ratios of 17.5:1 without the use of a choke. A/F ratios of 20:1 can be used without operational difficulties. Results with the Dresserator on the 1975 FTP are shown in Table 5.2.

Dresser claims 60% reductions in HC with the use of an enlarged exhaust manifold, presumably resulting in increased exhaust reactions.

TABLE 6.2

A. 1971 Ford Galaxie, 4,500 lb., 9:1 CR, 351 CID[45] (Tests at Dresser)

Baseline

HC	2-3	g/mi
CO	40	g/mi
NO_x	4-5	g/mi
MPG	10.5	

With Dresserator & Enlarged Exhaust Manifold

HC	0.3	g/mi
CO	4-5	g/mi
NO_x	1.2 - 1.7	g/mi
MPG	11	

With Dresserator
at A/F 18:1
No Vacuum Advance

HC	0.8 - 1	g/mi
CO	6 - 8	g/mi
NO_x	1 - 1.5	g/mi
MPG	11	

B. 1973 Chevrolet Monte Carlo, 4,500 lb., 350 CID, no EGR[46]
(Tests at GM) (Conventional Exhaust)

HC	0.849	g/mi
CO	3.95	g/mi
NO_x	1.915	g/mi
MPG	11.51	

C. Results from EPA (75 FTP)[47]

	HC	CO	NO_x	MPG
1973$_{V6}$ 2600cc, Ford Capri,^{r} retarded timing	0.68	5.8	1.21	18.2
Chevrolet Monte Carlo, retarded timing as above	1.11	5.1	1.56	12.8

REFS. 45, 46, 47

Ford currently has an extensive program underway to develop the Dresser type carburetor. Results at Ford with a 4,500 lb inertia-weight Galaxie, 351 CID, no EGR, indicate the following:[48]

HC	0.70 g/mi
CO	4.17 g/mi
NO_x	1.93 g/mi
MPG	10.7

(Results on 75 FTP)

In general terms, these results are consistent with those of GM, EPA and Dresser.

The versions of the Dresser carburetor used to obtain the data quoted above are mostly research tools, and not suitable for production. Many significant problem areas remain, including difficulties in precisely controlling the throat area with the large forces involved, wear of linkages and cams, correct location of fuel intake, and operation during unchoked conditions (wide-open throttle). Ford is working on three versions of the sonic carburetor, one with annular throat and two with rectangular throat. Several years of development effort are needed before this carburetor can be considered ready for large-scale production.

Nevertheless, the Dresserator system, without catalyst or EGR, can meet California 1975 standards, and, possibly with the addition of an exhaust thermal reactor and improved inlet manifold, meet levels of 0.41/3.4/2.0. Fuel economy at these emission levels should be equivalent to that of a 1975, 49-state model car.

7. DUAL CATALYST SYSTEMS

To reach levels of NO_x below 1.5 g/mi while retaining the basic components of the 1975 catalytic system will require the use of a reduction catalyst. The typical system will consist of a NO_x catalyst located near the engine exhaust manifold, an oxidation catalyst downstream, with air injection prior to the oxidation catalyst. Carburetion must be rich to provide a reducing atmosphere for the NO_x catalyst. In such systems, during the start-up phase, air is injected upstream of the NO_x catalyst, with the reduction bed acting as an oxidation catalyst during the start-up period.

F/A ratio must be carefully controlled for satisfactory operation of the NO_x catalyst. Too great an input of CO to the bed will lead to excessive formation of ammonia; too small a concentration of CO will not provide the correct reducing atmosphere required. Further, it is desirable to avoid lean transients when the catalyst is up to temperature, which may lead to excessive temperatures on the reduction bed and, at least for some catalysts, cause failure.

Several techniques have been used to control the ratio of CO to O_2 in the inlet gas stream to the reduction catalyst. Certainly, one way is the use of improved carburetors which much enable control of F/A to within 6% over the operating regimes of the vehicle. This has generally been the approach of the auto manufacturers, with results using noble-metal catalysts as shown in Table 7.1 below.

An accumulation of data on performance of NO_x converters developed by various catalyst manufacturers and tested on General Motors vehicles is shown in Figure 7.1[49] Even the most attractive catalyst from this chart, curve L, was over the CO standard after 8,000 miles (Figure 7.2).[50] More recent low-mileage data from GM on dual catalyst systems are shown in Table 7.2a,b. Fuel economy for the base 1975 vehicle is 12 mpg.[50] It can be seen that, for small cars, results on the best experimental vehicles indicate levels under 0.41/3.4/1.0 up to 10,000 to 20,000 miles with fuel economy between 0% and 5% worse than 1975

TABLE 7.1

Experimental Results - Dual Catalyst System

Manufacturer	Mileage	HC	CO	NOx
1. Ford Galaxie, 351 CID[49]	0	0.8	2.9	0.6
	9,000	1.2	6.2	0.7
2. Ford Galaxie, 351 CID[49]	0	0.7	3.0	0.7
	10,000	0.7	3.4	0.8
	22,000	1.0	7.0	1.0
3. Ford Galaxie, 400 CID[49]	0	0.6	0.9	0.4
	8,000	1.0	1.5	0.5
	12,000	1.2	2.0	0.7
4. General Motors, 5,000 IW 350 CID, EGR[50]	0	0.36	1.9	0.41
	3,000	0.41	2.4	0.56
5. General Motors, 5,000 IW, 350 CID, EGR[50]	0	0.31	2.8	0.24
	8,000	0.38	3.4	0.24
	12,000	0.94	4.4	0.38
	16,000	0.84	7.6	0.34
	20,000	0.66	3.4	0.36
	24,000	0.8	6.8	0.36
6. British Leyland, Austin Marina[51]	0	0.39	1.32	0.29
	6,740	0.53	1.71	0.27
	10,720	0.58	1.7	0.64
7. British Leyland, Austin Marina[51]	0	0.15	0.67	0.45
	10,875	0.38	1.8	0.85
8. British Leyland, Austin Marina[51]	0	0.19	2.49	0.35
	6,600	0.36	1.51	0.23
9. Nissan, 119 CID, Datsun[52] 2750 IW	0	0.09	1.08	0.33
	4,600	0.27	0.73	0.39
	11,700	0.30	0.93	0.48
	20,700	0.39	1.67	0.68
10. Nissan, 119 CID, Datsun[52] 2750 IW	0	0.21	1.38	0.30
	11,800	0.33	1.1	0.31
	18,300	0.57	4.07	0.39
11. Toyota, 2,500 IW, 1.6 liter[53]	0	0.11	1.89	0.43
	5,000	0.17	1.12	0.49

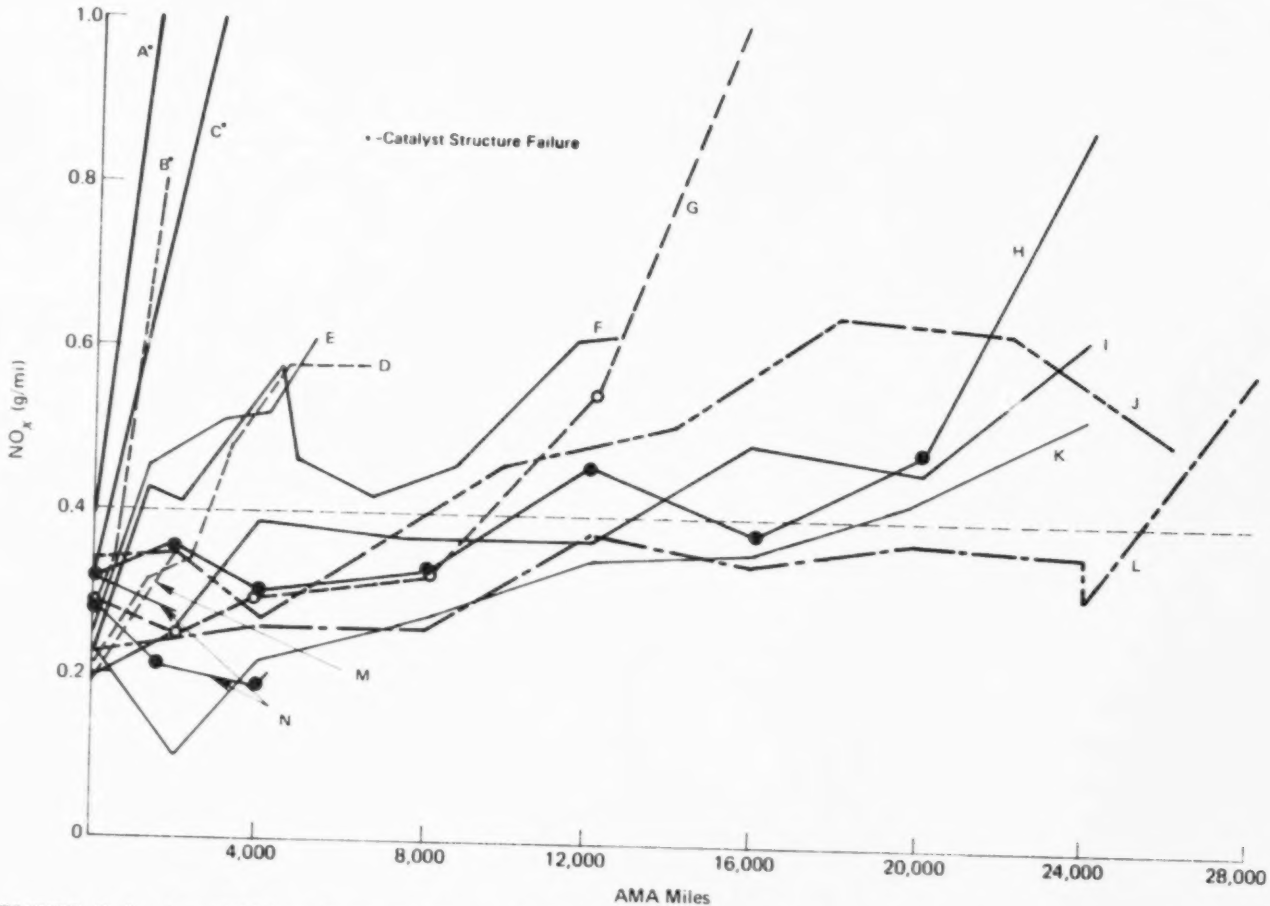


FIGURE 7.1 Durability Data on General Motors' NO_x Catalysts. Emission Durability Test Results, Dual Catalyst Emission Control Systems. 1975 Federal Test Procedure.

Source: Reference 50

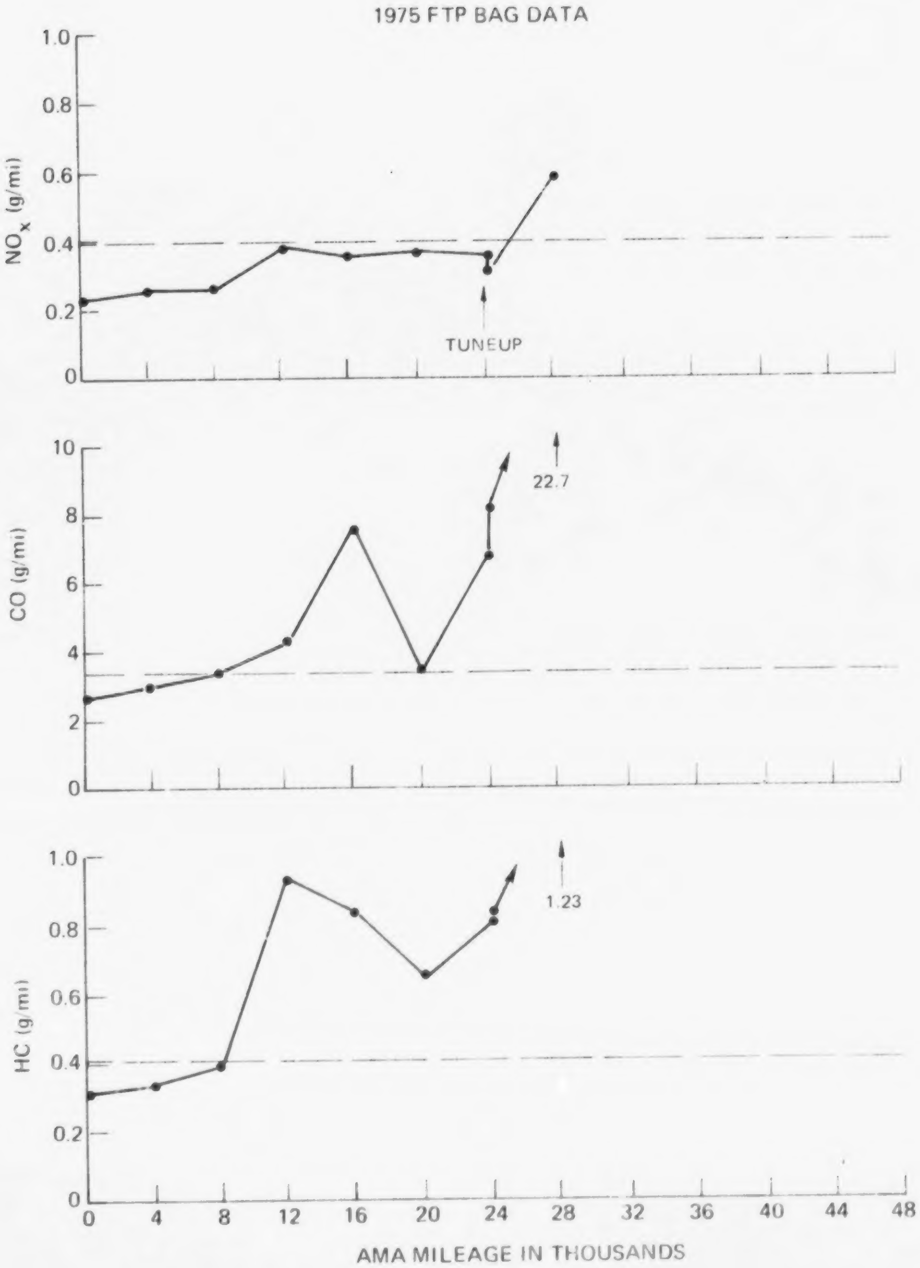


FIGURE 7.2 AMA Durability Test Oxidizing and Reducing Catalyst.

Source: Reference 50

TABLE 7.2a

Prototype

1977 Dual Catalyst System Performance

350 CID, 5,000 lb , EGR, Air, '75 FTP, Low Mileage

System	NO	HC	CO	NO_x	MPG
Developmental	6	0.33	2.5	0.35	11.8
		0.26/0.37	2.0/3.2	0.3/0.45	11.4/12.1
Durability	15	0.30	2.1	0.28	10.1
		0.17/0.48	1.1/3.8	0.19/0.35	8.7/12.4

TABLE 7.2b

18 Car Fleet
1977 Dual-Catalyst-System-Performance
350 CID, 5000 lb , EGR, Air, '75 FTP
A/F = 14/1

System	No.	Avg. Mileage	HC	CO	NO_x	MPG
Manifold + U.F.	12	231	0.36	1.9	0.41	8.5
			0.33/0.39	1.2/2.9	0.30/0.51	7.8/9.9
	1	3091	0.41	2.4	0.56	9.5
Manifold	6	314	0.29	2.3	0.58	9.3
			0.25/0.33	1.9/3.0	0.52/0.64	8.2/10.3

vehicles. Durability results are not as encouraging for large cars with higher engine NO_x emissions. The cause for the rapid decrease in NO_x converter efficiency with mileage accumulation is not well understood: how much is due to carburetion problems, or to poisoning or overtemperature is not precisely known.*

It appears that the amount of work and effort being performed on the dual-catalyst approach by the major manufacturers is somewhat diminished over that of two years ago. This may be due either to effort being pursued on other, more promising systems, or to a decision to wait with the expectation that alternate standards for NO_x will be legislated.

Other approaches involving the use of a reduction catalyst are being worked on by Gould and Questor. Each of these systems is designed to carefully control the CO/O_2 ratio to the NO_x catalyst. In the Gould system, an O_2 getter is used upstream of the reduction catalyst. In the current Gould configuration, the getter consists of a small, noble-metal oxidation catalyst. The getter is located in the same can as the metallic nickel-based NO_x converter, with an oxidation catalyst located downstream. The getter lowers the O_2 concentration entering the NO_x bed to approximately 0.1% over the range of operating conditions experienced in the CVS test (Figure 7.3). This would then compensate for the variabilities associated with today's conventional carburetors. The latest Gould reduction catalyst (GEM 68) gives over 90% next NO_x conversion (Fig. 7.4) when operating at 1250°F over a range of CO/O_2 of 2 to 6 (corresponding to A/F ratio of 14.2:12.7). Results of this system are given in Table 7.4.

To reduce HC levels to 0.41 g/mi, it would be necessary either to use a larger or improved oxidation catalyst or to improve

---

*To overcome problems associated with carburetor variability, GM has run a dual-catalyst system with feedback control featuring an oxygen sensor and variable Venturi carburetor (Table 7.3).

TABLE 7.3

1977 Dual Catalyst - Closed Loop System Performance

350 CID, 5,000 LB Inertia Weight with
Oxygen Sensor and Variable Venturi Carburetor

Low Mileage (Average of Two Tests)

HC	CO	NO_x	MPG
0.27	0.83	0.25	11.9

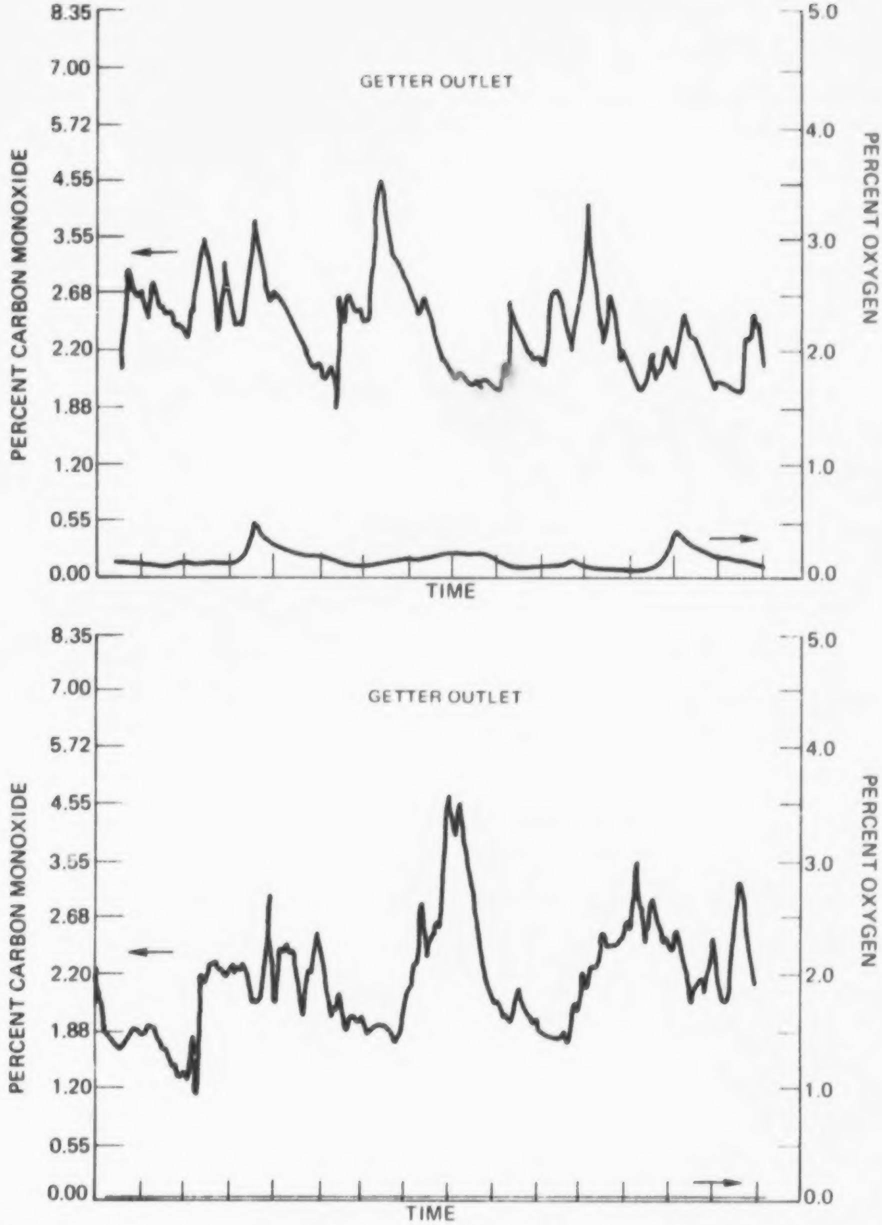


FIGURE 7.3 Effect of Getter on Inlet CO and O_2 During Portion of CVS Test. Test Conducted on 351 CID Ford Torino, Automatic Transmission.

Source: Reference 54

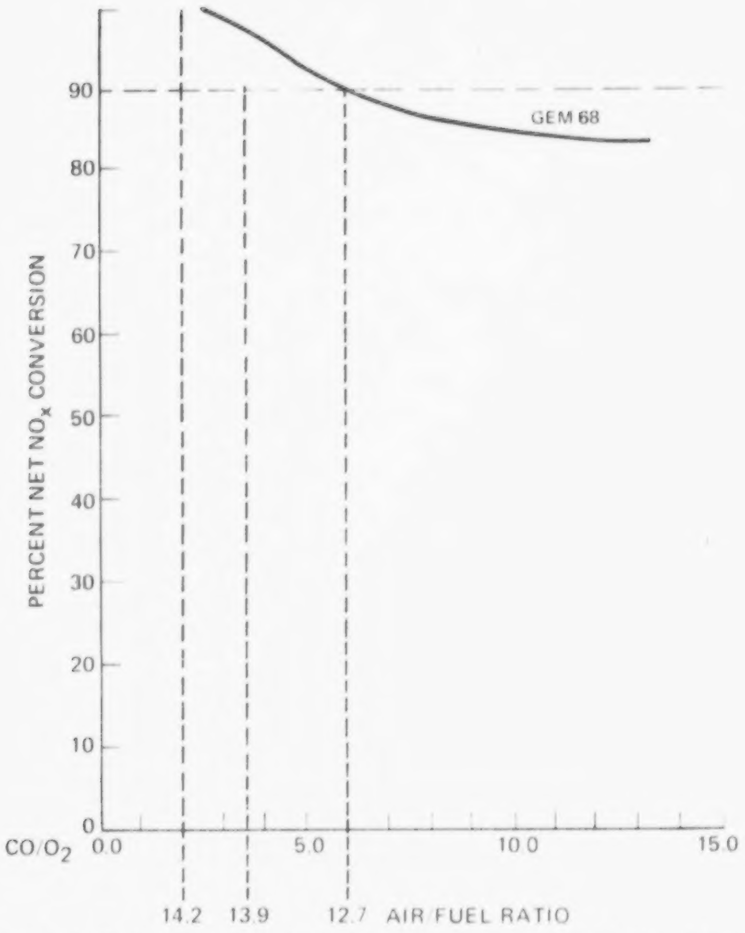


FIGURE 7.4 Typical Net NO_x Conversion as a Function of Air/Fuel Ratio for a Gem 68.

Source: Reference 54

TABLE 7.4

Vehicle	Mileage	Net NO_x Conversion Efficiency	CO	NO_x	HC*
73 Datsun 610, IW 2,500 lbs.	5,600	85.2	3.149	0.354	
No EGR, Manual Transmission	10,249	86.0	1.917	0.356	
Test at Gould	15,381	84.5	1.906	0.384	
	25,580	85.5	3.18	0.382	

*HC were measured incorrectly and are not included.

	HC	CO	NO_x	Economy
Same, Test at EPA after				
25,580 miles	0.98	2.93	0.41	21.5 MP
Average of 3 tests				

REF. 55

carburetion. Both approaches are now being pursued by Gould.

Preliminary results with the Gould system on a large car, 1971 Ford Torino, indicate NO_x levels of approximately 0.6 g/mi up to 25,000 miles, with no EGR. Fuel economy of the large car was equivalent to that of a 1973 model. Gould's experimentation to date has been with stock vehicles, retaining timing while resetting the carburetors to give the desired rich carburetion. It would appear that if this system were to be applied to a 1975 vehicle with timing and other adjustments for optimum economy, some improvements in economy would be attained. Conservatively, it would appear that levels of 0.4/3.4/1.0 in standard vehicles could be realized with economy no worse than 5%-10% below 1975 catalyst vehicles. For small cars, 0.41/3.4/0.4 could be attained with the Gould system with economy approximately the same as 1975 models of the same weight.

With the Questor approach, the ratio of CO/O_2 going to the NO_x converter is controlled with a rich thermal reactor instead of a getter. Thus, the Questor system consists of a rich thermal reactor, followed by a metallic, nickel-based NO_x converter, followed by another thermal reactor for cleanup of HC and CO. Controlled air is injected into the exhaust ports and before the final oxidizing thermal reactor. Durability tests of the Questor system are shown in Table 7.5. Fuel economy was 8.2 mpg, about 14% worse than EPA results for average 1974 vehicles in the 5,000-pound weight class.

Questor is currently testing a newer, more durable reduction catalyst which will enable leaner operation (although still on the rich side of stoichiometric). Results on a Datsun tested at 2,750-pound inertia weight gave, at 8,103 miles:

HC	0.16
CO	2.97
NO_x	0.28

TABLE 7.5

Questor System on 1971, 400 CID Pontiac Catalina

Mileage	HC	CO	NO_x	Comments
0	0.085	3.03	0.365	
18,483	0.400	2.66	0.380	
23,142	0.235	1.56	0.617	NO_x catalyst replaced
35,946	0.158	3.045	0.419	
50,024	0.294	2.986	0.283	

REF. 56

Economy here was 18.2 mpg, about equivalent to that of the average 1974 vehicle in that class.

It is felt that improved carburetion could help economy of both the Gould and Questor systems. Both systems appear capable of being certified at levels below 0.41/3.4/1.0.

8. THREE-WAY CATALYST WITH FEEDBACK

8.1 Introduction

Under carefully controlled conditions, a single-bed catalyst is able to reduce all three automotive emissions, HC, CO and NO_x, to levels of 0.41, 3.4 and 0.4 g/mi, respectively. Current three-way catalysts of this type must be operated with the engine close to stoichiometric, as shown in Figure 8.1.[57] Control to within ± 0.1 A/F ratio is required for successful operation. With the successful development of the O_2 sensor and feedback control, which allows the required A/F ratio control (Section 5) intensive efforts are underway to develop a three-way catalyst with the required durability. This three-way catalyst system with feedback has several advantages over a dual catalyst system: with only one catalyst, the problem of catalyst warm-up and cold-start emissions is alleviated; operation at stoichiometric rather than fuel-rich leads to improved fuel economy; no air pump is required since enough O_2 is present in the exhaust stream; and, feedback control at stoichiometric provides a self-maintaining feature, compensating for minor variations in engine parameters.

8.2 Three-Way Catalyst with Electronic Fuel Injection (EFI) and Feedback

Many manufacturers have been able to achieve 1978 levels at low mileage, using the O_2 sensor feedback and L-jetronic fuel injection. Typical results are shown in Table 8.1.[58]

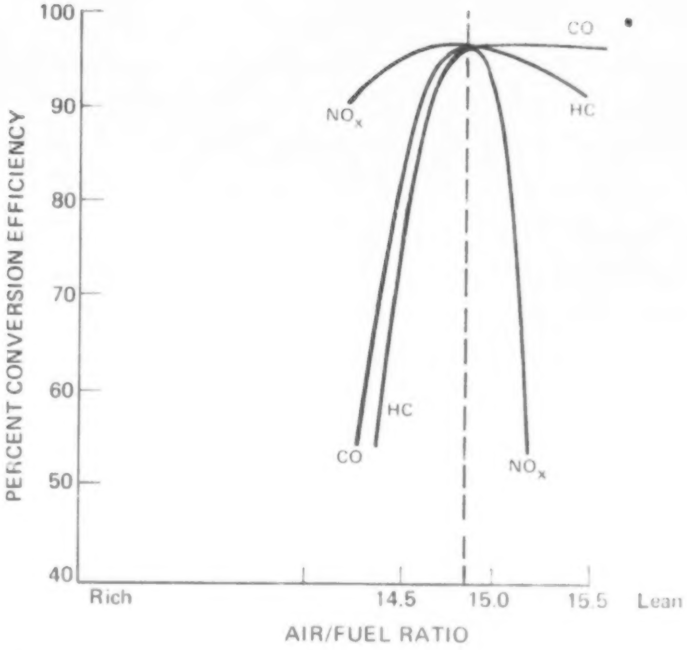


FIGURE 8.1 Conversion Efficiency of a Three-Constituent Catalyst.

Source: Reference 57

TABLE 8.1

	HC	CO	NO_x	
Volkswagen	0.3	1.2	0.2	
Bosch	0.3	1.7	0.3	4 cylinder, 1.9 liter
Daimler-Benz	0.4	1.8	0.4	8 cylinder, 4.8 liter

Robert Bosch has the most advanced durability results and claims that 20,000-mile durability has been demonstrated with a 2,300 lb car and 1.9 liter engine with the values shown in Figure 8.2. After that period, the NO_x emissions started to rise for unknown reasons. Bosch also made the claim, based on the results of bench tests (Figure 8.3), that better catalysts are now available and that durability of 25,000 miles or more will soon be demonstrated. The data of Figure 8.2 were obtained with the catalyst dated 10/10/73 in Figure 8.3; the catalyst dated 4/2/74 clearly exhibits better performance.[59]

Ford[60] has been experimenting with an in-house developed EFI system and 0_2 feedback with the following results for a fresh catalyst:

	HC	CO	NO_x
Feed gas	2.9	22	4.2
After catalyst	0.1	2.0	0.5
No EGR			

and for aged catalyst (100 hrs)

	HC	CO	NO_x
Feed gas	3.18	24	5.0
After Catalyst	0.11	0.68	1.34
No EGR			

Life tests continue.

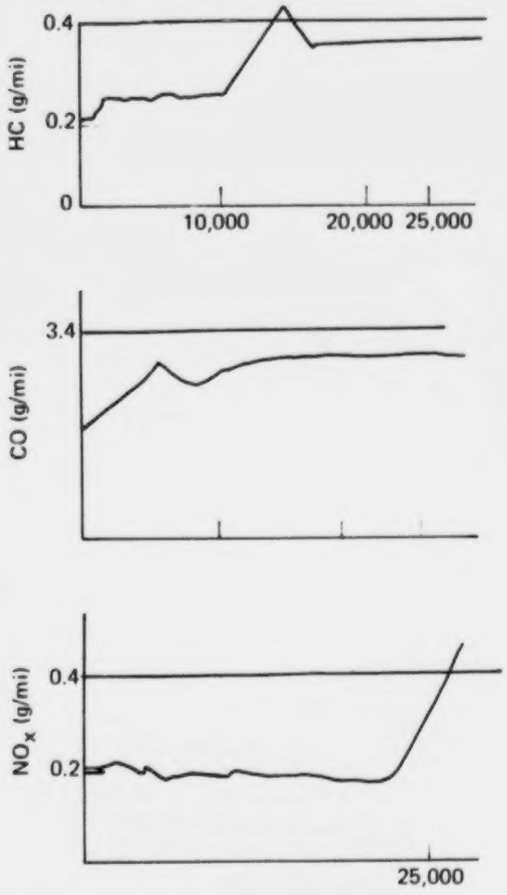


FIGURE 8.2 4-Cylinder Engine, 1.9 Liter, L-Jetronic, DeGussa OM721, Fuel Economy 18.7 mpg, Weight of Car 1050 kg.

Source: Reference 59

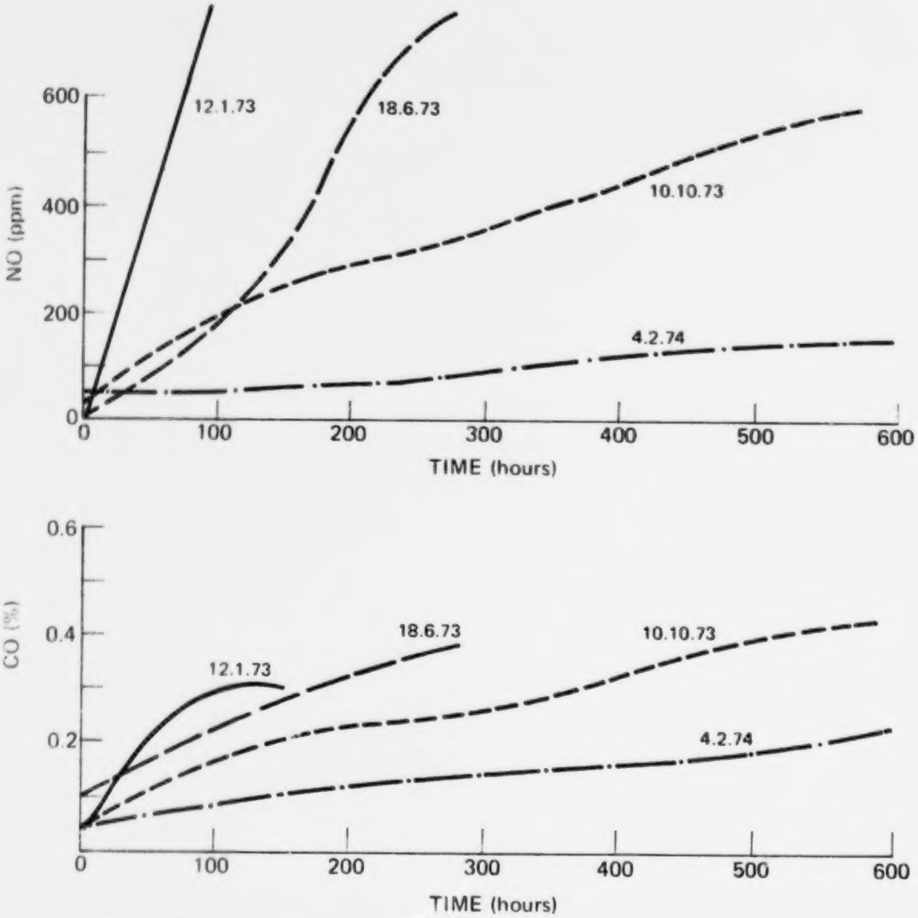


FIGURE 8.3 Catalyst Durability.

Source: Reference 59

TABLE 8.2

a. Vega EFI Emission and Economy Results (Low Mileage)

3000 lb I.W.

	HC	CO	NO_x
Average of 5 emissions tests:	0.23 g/mi	2.58 g/mi	0.32 g/mi

Fuel Economy: 20.43 mpg @ 0.35 g/mi ← NO_x(EGR)
21.42 mpg @ 0.90 g/mi ← NO_x(No EGR)

Base: 20.50 mpg for '75 Calif. @ 1.4 NO_x
20.32 mpg for '75 Federal @ 2.1 NO_x

b. Chevrolet 350 C.I.D., V8, 4,500 lb I.W. (Low Mileage)

HC	CO	NO_x	MPG
0.56	5.1	0.96	11.5
0.47	4.6	0.77	Not available

REF. 57

TABLE 8.3

Comparison of Various Control Schemes (1.9 L Engine)
All Cars Equipped with L-Jetronic

	Car 1	Car 2	Car 3*	Car 4*
Stoichiometric	1975 Model	Lean	Lean	
Ratio	1.05	1.15-1.2	1.04	1.0
Spark Advance	4°	8° Double ignition	8°	4° delay
Percent EGR	3-10	8	8	0

---

*Cars 3 and 4 have feedback control

HC	0.57	0.15	0.2	0.15
CO	6.67	2.9	3.02	1.72
NO_x	1.5[illegible]	0.88	1.16	0.13
Fuel Cons.	100%	121%	100%	89%

General Motors[57] provided data on a Vega equipped with a three-way catalyst, EFI and feedback as shown in Table 8.2.

Most manufacturers agree that fuel economy of the O_2 sensor - L-jetronic feedback control is improved over open-loop controls and that 1978 standards can be met with minimum fuel penalty if the three-way catalyst aging problem is resolved.

Bosch provides an interesting comparison of various control systems in Table 8.3. The superiority of feedback is evident.

8.3 Three-Way Catalyst with Mechanical Fuel Injection (MFI) and Feedback

The O_2 sensor output requires the addition of a simple electronic control unit and an additional solenoid-operated fuel pump to modulate fuel pressure in the control pressure loop of the K-jetronic mechanical fuel injection device. The O_2 sensor feedback system with K-jetronic now becomes somewhat more expensive than the equivalent L-jetronic feedback control.

Many manufacturers report that they were able to achieve 1978 NO_x standards at low mileage; however, failure occurred because of three-way catalyst aging after less than 10,000 miles. Typical results are shown in Table 8.4.

Table 8.4[58]

	HC	CO	NO_x	MPG
Saab	0.1	1.7	0.21	19.3
Audi	0.28	1.0	0.4	
Volvo	0.25	0.8	0.25	16.0

No durability data is available.

No U.S. manufacturer reported data with the K-jetronic feedback system.

8.4 Three-Way Catalyst with Carburetor and Feedback

All U.S. manufacturers and some foreign carburetor manufacturers are developing carburetors whose settings can be continuously adjusted with electrical error signals from an exhaust gas sensor. Most electronic carburetors are of the variable Venturi category although some work is reported with sonic carburetion. This approach is logical since feedback control makes sense only with better cylinder-to-cylinder distribution than can be achieved with conventional carburetors. VV carburetors, sonic carburetors, and hot-spot carburetors can provide the needed improved A/F ratio distribution.

Results from GM with advanced design carburetors, feedback and the three-way catalyst are given in Table 8.5[57] (all at low mileage).

TABLE 8.5

Car	Carburetor	HC	CO	NO_x	MPG
4000 I.W., V8	Mod. Quad	0.28	4.85	0.54	11.7
4500 I.W., V8, 350 CID	IFC	0.17	5.5	0.69	11.5

To summarize:

- In all cases, fuel economy of three-way catalyst systems is good, as is driveability. Fuel economy could be improved further by the complete elimination of EGR; this may not be possible with the large U.S. engines.
- The durability of the O_2 sensor is established; the durability of the three-way catalyst is not proven and cannot be predicted. The tests of Bosch suggest, however, that a durable catalyst may be achievable.

- The cost of feedback control systems may be attractive in comparison with more conventional systems because of possible elimination of many presently used ancillary controls such as fast chokes, altitude compensation, air pumps, EGR, etc.
- The feedback control is a new technology with great potential to achieve low emissions with low fuel consumption and control-system cost.

9. ROTARY ENGINES

9.1 Introduction

The chief advantages of the rotary engine as an automotive power plant lie in its smoother operation, fewer number of parts and higher power-to-weight ratio, in comparison to a conventional piston engine. However, the engine has a high surface-to-volume ratio, contributing to higher HC emissions and lower thermal efficiencies in comparison to equivalent piston engines. Bare-engine HC emission levels of current rotary engines are approximately four times those of equivalent piston engines, whereas CO and NO_x levels are roughly the same as those of piston engines.

The emissions-control system used on 1974 Mazda rotary engines featured a rich exhaust thermal reactor to control HC emissions, with the engine operating at an air fuel ratio of approximately 13:1. Exhaust emissions measured in 1974 California certification by EPA are given in Table 9.1, as well as data from Toyo Kogyo on the same model.

Because of the above-cited problem with high HC emissions and high fuel consumption, there does not appear to be a concerted movement in the industry towards rotary engines. Though a few manufacturers have increased their efforts on rotary engines, most of the increased effort has gone into feasibility studies. Ford has terminated such a feasibility study during the past year.

9.2 Near-Term Systems

Emissions-control systems currently used on rotary engines are similar to those used on conventional piston engines; namely, catalysts or thermal reactors and EGR. There is some concern about the durability of the catalyst-equipped systems since the HC loading is so much higher than that of conventional engines. Figure 9.1 illustrates this problem. With base-engine emissions of 8-10 g/mi HC catalytic converter efficiencies of approximately 90% are required

TABLE 9.1

Exhaust Emissions of the 1974 Mazda with Rich Thermal Reactor

	HC	CO	NO_x	MPG
1974 California EPA certification	2.4	19	0.9	10.4
1974 Production average	2.5	14	1.3	11.8

3,000 lb inertia weight

Engine displacement 80 CID

Manual transmission

REFS. 61,62

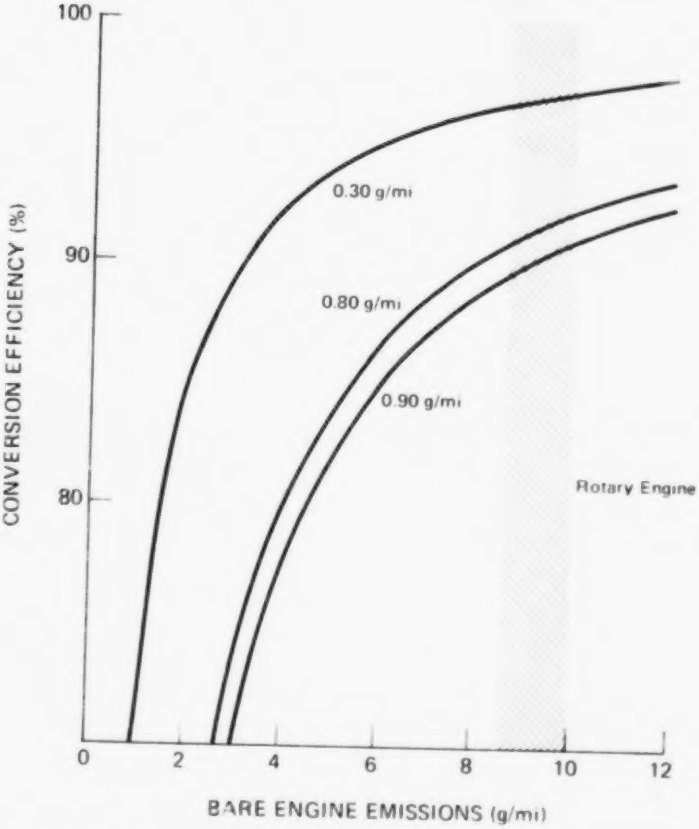


FIGURE 9.1 HC Conversion Efficiency Requirements.

Source: Reference 63

to achieve exhaust HC levels of 0.90 g/mi (California interim 1975 level). There is clearly little margin for deterioration.

Thermal reactor systems do not appear to have this problem; deterioration factors for these systems are shown in Table 9.2. However, the rich reactors currently in use incur a fuel penalty, as was shown in Table 9.1. A summary of results from General Motors is given in Table 9.3. It can be seen that, at least at low mileage, fuel economy of catalyst-equipped rotary engines approaches that of equivalent 1975 vehicles equipped with conventional engines.

Toyo Kogyo is developing a lean-reactor system. This system uses an A/F ratio of 16.5:1 to 17:1. Results are shown in Table 9.4.

9.3 Long-Term Systems

Some work is being done on more advanced rotary engines systems. Most of this effort is being spent on adapting the stratified-charge concepts to the rotary engine. Both open-chamber and divided-chamber concepts have been tried with reasonable results. Table 9.5 shows the outcome of some of this work.

Figure 9.2 shows the relationship between NO_x level and fuel consumption for a typical present rotary-engine powered vehicle and similar stratified-charge rotary-engine vehicles. Although a significant fuel-consumption improvement is made using the stratified-charge principles, the basic relationship between NO_x level and fuel consumption holds. Whenever lower NO_x levels are approached, the driveability is seriously impaired even with the stratified-charge systems.

Although the stratified-charge work has shown promising results, it is still in the early stages of development. Also, some type of external clean-up device (i.e., thermal reactor, catalyst, etc.) is still needed to achieve the emissions standards although the bare-

TABLE 9.2

Typical Deterioration Factors of Thermal Reactor-Equipped Rotary Engines

Pollutant	Deterioration Factor
HC	1.0 - 1.05
CO	1.0 - 1.03
NO_x	1.02 - 1.05

TABLE 9.3

Emissions Summary

System	Tail Pipe HC	Tail Pipe CO	Tail Pipe NOx	Base Engine HC	Base Engine CO	Base Engine NOx	EPA MPG
350 V-8 -- 260 Cu. In. U'Floor Bead Converter[62]	0.29	1.88	2.3	2.7	8.4	2.3	
GMRE -- 260 Cu. In. U'Floor Bead Converter[63]	0.60	1.2	2.6	10.9	8.1	2.4	15.0/15.5
GM RE, U'Floor & Warm-Up Conv.	0.30	4.6	1.5	10.7	21.5	1.3	15.0/15.5
GM RE, Reactor/Conv. System	0.40	2.5	2.1	3.3	14.5	2.1	14.3
GM RE, Reactor Only	0.46	6.6	1.7				12.4

1 - low mileage

2 - 4,000 lb weight class

3 - 3,500 lb weight class

4 - Base engine values were measured at the reactor outlet

REF. 63, 64

TABLE 9.4

Rotary with Lean Reactor

	Emission Target (HC, CO, NO_x, g/mi)	Actual Emissions (CO, HC, NO_x, g/mi)	Fuel Economy mpg	No. of Tests
No EGR	0.9/9/2.0	4.8/0.38/1.7	17.0	5
No EGR	0.41/3.4/2.0	2.0/0.18/1.7	16.4	3
EGR		2.4/0.21/0.85	15.3	3
EGR		2.3/0.27/0.74	15.1	2

I.W. = 3,000 lbs.

Manual Transmission

Engine displacement 80 C.I.D.

REF. 62

TABLE 9.5

Emission and Fuel Consumption Characteristics of an Experimental Open-Chamber Stratified-Charge Rotary Engine

EGR (%)	0	7-8%	20%*
HC (g/mi)	0.24	0.22	
CO (g/mi)	1.8	2.5	
NO_x (g/mi)	1.5	0.91	0.4
Fuel Consumption (mpg)	17.5	16.8	14.0

* Bench data only

REF. 64

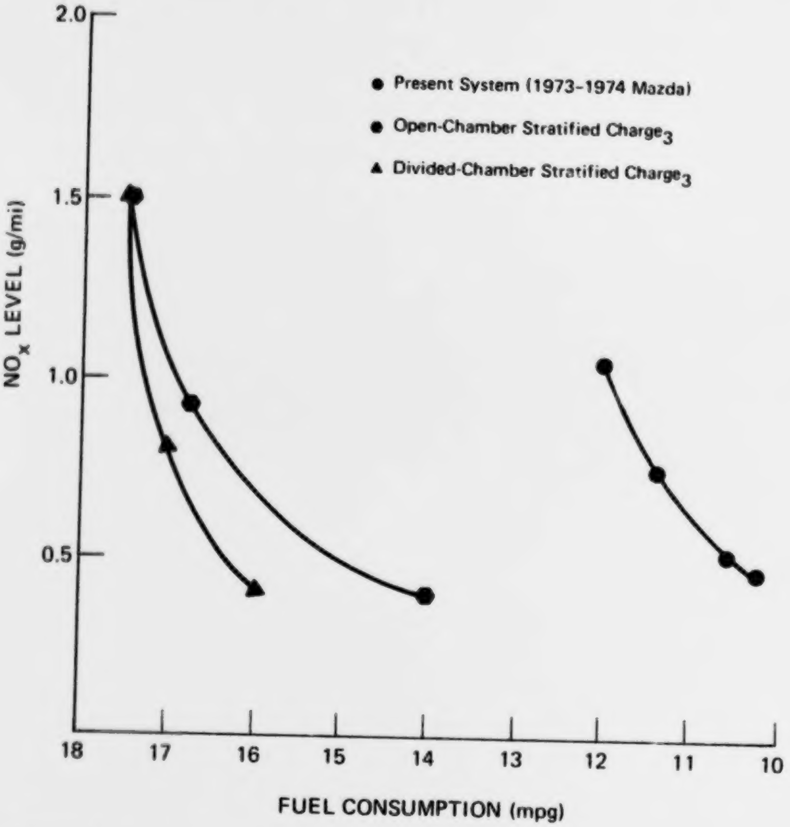


FIGURE 9.2 Comparison of NO_x and Fuel Consumption Characteristics of Various Rotary Engine Concepts.

Source: References 62, 63

engine emissions are undoubtedly lower. It is doubtful if a fully developed stratified-charge rotary-engine could be available before the early to middle 1980's.

9.4 Summary

Most of the rotary-engine effort to date has been concentrated on improving durability and fuel consumption. Little effort has been spent on understanding the basic combustion process or lowering the bare-engine emissions. Most manufacturers appear to be looking at the rotary engine for its packaging, performance and potential cost advantages rather than as a solution to the emissions problem.

It appears that rotary-engine systems can meet near-term emissions standards with reasonable fuel consumption. Although the advanced stratified-charge rotary-engine concepts appear promising, it is doubtful whether they can be available until the 1980's.

10. STRATIFIED-CHARGE ENGINES

10.1 Introduction and General Background

a. General -- The term "stratified-charge engine" has been used for many years in connection with a variety of unconventional engine combustion systems. Common to nearly all such systems is the combustion of F/A mixtures having a significant gradation or stratification in fuel concentration within the engine combustion chamber. Hence the term "stratified charge." Historically, the objective of stratified-charge-engine designs has been to permit spark-ignition-engine operation with average or overall F/A ratios lean beyond the ignition limits of conventional combustion systems. The advantages of this type of operation will be enumerated shortly. Attempts at achieving this objective date back to the first or second decade of this century.[65]

More recently, the stratified-charge engine has been recognized as a potential means for control of vehicle pollutant emissions with minimum loss of fuel economy. As a consequence, the various stratified-charge concepts have been the focus of renewed interest.

b. Advantages and disadvantages of lean-mixture operation -- Fuel-lean combustion as achieved in a number of the stratified-charge-engine designs receiving current attention has both advantages and disadvantages when considered from the combined standpoints of emissions control, vehicle performance and fuel economy.

Advantages of lean mixture operation include the following:

- Excess oxygen contained in lean-mixture combustion gases help to promote complete oxidation of hydrocarbons (HC) and carbon monoxide (CO) both in the engine cylinder and in the exhaust system.

- Lean-mixture combustion results in reduced peak engine-cycle temperatures and can, therefore, yield lowered nitrogen oxide (NO_x) emissions.
- Thermodynamic properties of lean-mixture-combustion products are favorable from the standpoint of engine-cycle thermal efficiency (reduced extent of dissociation and higher effective specific heats ratio).
- Lean-mixture operation can reduce or eliminate the need for air throttling as a means of engine load control. The consequent reduction in pumping losses can result in significantly improved part-load fuel economy.

Disadvantages of lean mixture operation include the following:

- Relatively low-combustion gas temperatures during the engine cycle expansion and exhaust processes can result from extremely lean operation. As a consequence, HC oxidation reactions are retarded and unburned HC exhaust emissions can be excessive.
- Engine modifications aimed at raising exhaust temperatures for improved HC emissions control (retarded ignition timing, lowered compression ratio, protracted combustion) necessarily impair engine fuel economy.
- If lean-mixture operation is to be maintained over the entire engine load range, maximum power output and, hence, vehicle performance are significantly impaired.
- Lean-mixture exhaust gases are not amenable to treatment by existing reducing catalysts for NO_x emissions control.

- Lean-mixture combustion, if not carefully controlled, can result in formation of undesirable odorant materials that appear in significant concentrations in the engine exhaust. Diesel exhaust odor is typical of this problem and is thought to derive from lean-mixture regions of the combustion chamber.
- Measures required for control of NO_x emissions to low levels (for example, EGR) can accentuate the above HC and odorant emissions problems.

Successful development of the several stratified-charge-engine designs now receiving serious attention will depend very much on the balance that can be achieved among the foregoing favorable and unfavorable features of lean combustion. This balance will, of course, depend ultimately on the standards or goals that are set for emissions control, fuel economy, vehicle performance and cost. Of particular importance are the relationships between three factors--unburned hydrocarbon (UBHC) emissions, NO_x emissions, and fuel economy.

c. Stratified-charge-engine concepts -- Charge stratification permitting lean-mixture operation has been achieved in a number of ways using differing concepts and design configurations.

Irrespective of the means used for achieving charge stratification, two distinct types of combustion processes can be identified. One approach involves ignition of a small and localized quantity of flammable mixture which, in turn, serves to ignite a much larger quantity of adjoining or surrounding fuel-lean-mixture--too lean for ignition under normal circumstances. Requisite mixture stratification has been achieved in several different ways ranging from use of fuel injection directly into "open" combustion chambers to use of dual combustion chambers divided physically into rich and lean-mixture regions. Under most operating conditions, the overall or average F/A ratio is fuel-lean and the advantages enumerated above for lean operation can be realized.

A second approach involves timed staging of the combustion process. An initial rich-mixture stage in which major combustion reactions are completed is followed by rapid mixing of rich-mixture combustion products with an excess of air. Mixing and the resultant temperature reduction can, in principle, occur so rapidly that minimum opportunity for NO formation exists and, as a consequence, NO_x emissions are low. Sufficient excess air is made available to encourage complete oxidation of HC and CO in the engine cylinder and exhaust system. The staged combustion concept has been specifically exploited in divided-chamber or large-volume prechamber engine designs. But it will be seen that staging is also inherent to some degree in other types of stratified-charge engines.

The foregoing would indicate that stratified-charge engines can be categorized either as "lean-burn" engines or "staged-combustion" engines. In reality, the division between concepts is not so clear cut. Many engines encompass features of both concepts.

d. Scope -- During the past several years, a large number of engine designs falling into the broad category of stratified-charge engines have been proposed. Many of these have been evaluated by competent organizations and have been found lacing in one or more important areas. A much smaller number of stratified-charge engine designs have shown promise for improved emissions control and fuel economy with acceptable performance, durability and production feasibility. These are currently receiving intensive research and/or development efforts by major organizations--both domestic and foreign.

The purpose of this Consultant Report is not to enumerate and describe the many variations of stratified-charge engine design that have been proposed in recent years. Rather, it is intended to focus on those engines that are receiving serious development efforts and for which a reasonably large and sound body of experimental data has evolved. It is hoped that this approach will lead to a reliable appraisal of the potential for stratified-charge engine systems.

10.2 Open-Chamber, Stratified-Charge Engines

a. General -- From the standpoint of mechanical design, stratified-charge engines can be conveniently divided into two types: open-chamber and dual-chamber. The open-chamber, stratified-charge engine has a long history of research interest. Those engines reaching the most advanced stages of development are probably the Ford-programmed combustion process (PROCO)[66,67] and Texaco's controlled combustion process (TCCS).[68,69] Both engines employ a combination of inlet air swirl and direct timed combustion-chamber fuel injection to achieve a local fuel-rich ignitable mixture near the point of ignition. For both engines, the overall mixture ratio under most operating conditions is fuel lean.

Aside from these general design features that are common to the two engines, details of their respective engine-cycle processes are quite different, and these differences affect engine performance and emissions characteristics.

b. The Ford PROCO engine

(1) Descriptions -- The Ford PROCO engine is an outgrowth of a stratified-charge development program initiated by Ford in the late 1950's. The development objective at that time was an engine having diesel-like fuel economy but with performance, noise levels, and driveability comparable to that of conventional engines. In the 1960's, objectives were broadened to include exhaust-emissions control.

A recent developmental version of the PROCO engine is shown in Figure 10-1. Fuel is injected directly into the combustion chamber during the compression stroke resulting in vaporization and formation of a rich mixture cloud or kernel in the immediate vicinity of the spark plug(s). A flame initiated in this rich-mixture region propagates outwardly to the increasingly fuel-lean regions of the chamber. At the same time, high air-swirl velocities resulting from special orientation of the air inlet system help to promote rapid mixing of fuel-rich combustion products with excess air contained in the lean region. Air swirl is augmented by the "squish" action of the piston as it approaches the combustion-chamber roof at the end of the compression stroke. The effect of rapid mixing can be viewed as promoting a second stage of combustion in which rich mixture-zone products mix with air contained in lean regions. Charge stratification permits operation with very lean F/A mixtures with attendant fuel economy and emissions advantages. In addition, charge stratification and direct fuel injection permit use of high compression ratios with gasolines of moderate octane quality -- again giving a substantial fuel economy advantage.

Present engine operation includes enrichment under maximum power-demand conditions to mixture ratios richer than stoichiometric. Performance, therefore, closely matches that of conventionally powered vehicles.

Nearly all PROCO development plans at the present time include use of oxidizing catalysts for HC emissions control. For a given HC emissions standard, oxidizing catalysts permit use of leaner A/F ratios (lower exhaust temperatures) together with fuel injection and ignition timing characteristics optimized for improved fuel economy.

(2) Emissions and fuel economy -- Figure 10-2 is a plot of PROCO vehicle fuel economy versus NO_x emissions based on the

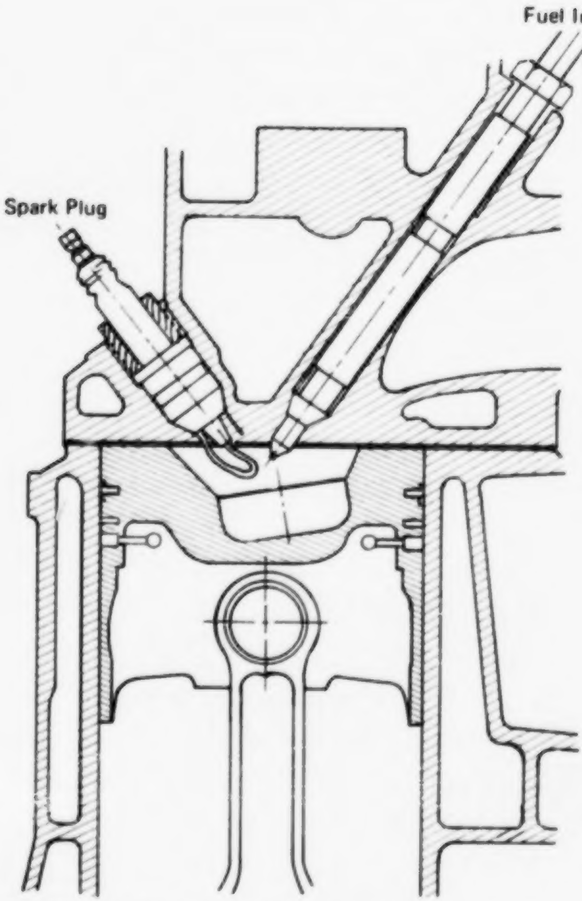

Fuel Injector
Spark Plug

FIGURE 10.1 Ford PROCO Engine.

Source: Reference 71

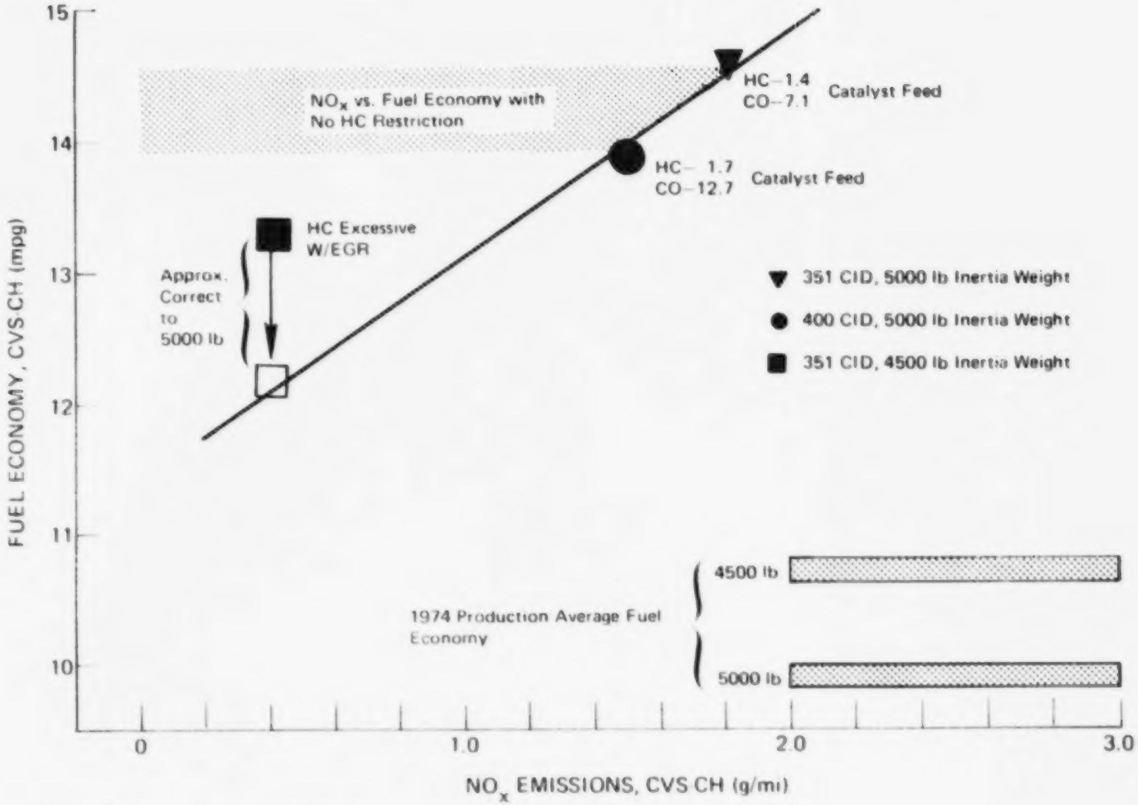


FIGURE 10.2 Ford PROCO Engine Fuel Economy and Emissions.

Source: References 70, 71

Federal CVS-CH test procedure. Also included are corresponding HC and CO emissions levels. Only the most recent test data have been plotted since these are most representative of current program directions and also reflect most accurately current emphasis on improved vehicle fuel economy.[70,71] For purposes of comparison, average fuel economies for 1974 production vehicles weighing 4,500 pounds and 5,000 pounds have been plotted.[72] (The CVS-C values reported in Reference 72 have been adjusted by 5% to obtain estimated CVS-CH values.)

Data points to the left on Figure 10-2 at the 0.4 g/mi NO_x level represent efforts to achieve statutory 1977 emissions levels.[70] While the NO_x target of 0.4 g/mi was met, the requisite use of EGR resulted in HC emissions above the statutory level.

A redefined NO_x target of 2.0 g/mi has resulted in the recent data points appearing in the upper right-hand region of Figure 10-2.[71] The HC and CO emissions values listed are without exhaust oxidation catalysts. Assuming catalyst conversion efficiencies of 50%-60% at the end of 50,000 miles of operation, HC and CO levels will approach but not meet statutory levels. At the indicated levels of emissions-control fuel economy is improved some 40% to 45% relative to 1974 production-vehicle averages for the same weight class.

The cross-hatched, horizontal band appearing across the upper part of Figure 10-2 represents the reductions in NO_x emissions achievable with use of EGR is HC emissions are unrestricted. The statutory 0.4 g/mi level can apparently be achieved with this engine with little or no loss of fuel economy but with significant increases in HC emissions. The HC increase is ascribed to the quenching effect of EGR in lean-mixture regions of the combustion chamber.

(3) Fuel requirements -- Current PROCO engines operated with 11:1 compression ratio yield a significant fuel economy advantage over conventional production engines at current compression ratios. According to Ford engineers, the PROCO engine at this compression ratio is satisfied by typical full-boiling commercial gasolines of 91 RON rating. Conventional engines are limited to compression ratios of about 8:1 and possibly less for operation on similar fuels.

Results of preliminary experiments indicate that the PROCO engine may be less sensitive to fuel volatility than conventional engines--an important factor in flexibility from the standpoint of the fuel supplier.

(4) Present status -- Present development objectives are two-fold:

- Develop calibrations for alternate emissions target levels to determine the fuel economy potential associated with each level of emissions control.
- Convert engine and auxiliary systems to designs feasible for high-volume production.

c. The Texaco TCCS stratified-charge engine

(1) General description -- Like the Ford PROCO engine, Texaco's TCCS system involves coordinated air swirl and direct combustion-chamber, fuel injection to achieve charge stratification. Inlet-port-induced cylinder air swirl rates typically approach ten times the rotational engine speed. A sectional view of the TCCS combustion chamber is shown in Figure 10-3.

Unlike the PROCO engine, fuel injection in the TCCS engine begins very late in the compression stroke -- just before the desired time of ignition. As shown in Figure 10-4, the first portion

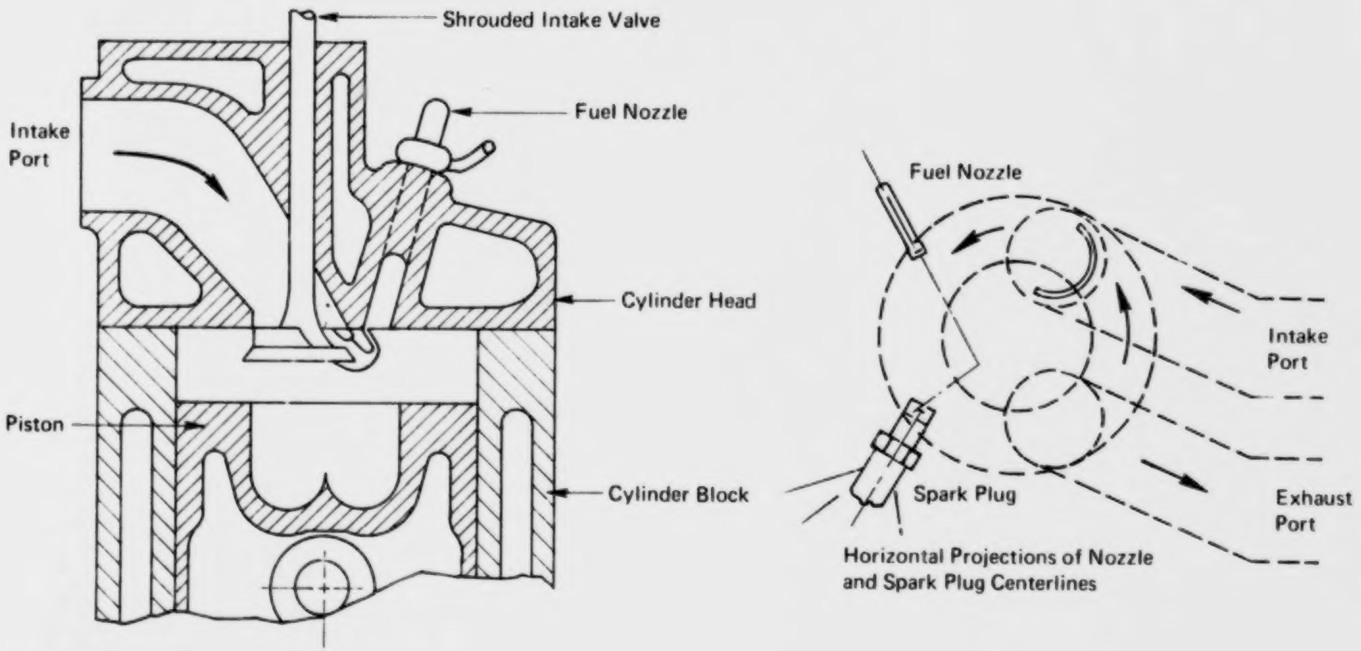

Shrouded Intake Valve
Fuel Nozzle
Intake Port
Cylinder Head
Piston
Cylinder Block
Fuel Nozzle
Intake Port
Spark Plug
Exhaust Port
Horizontal Projections of Nozzle and Spark Plug Centerlines

FIGURE 10.3 Texaco TCCS Engine.

Source: Reference 73

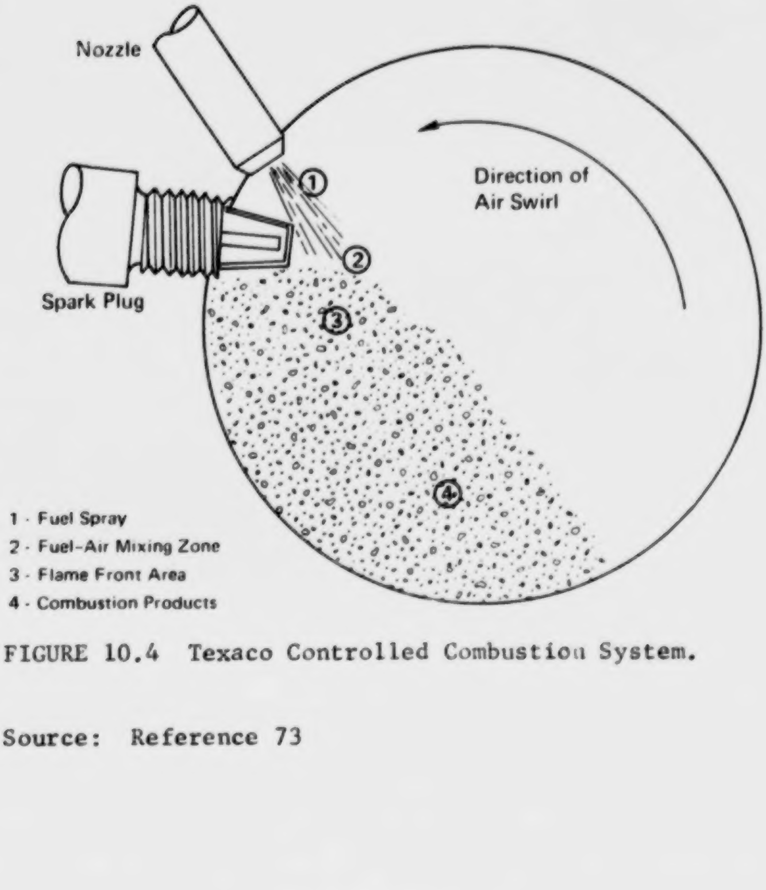

Nozzle
Spark Plug
Direction of Air Swirl
①
②
③
④
1 - Fuel Spray
2 - Fuel-Air Mixing Zone
3 - Flame Front Area
4 - Combustion Products

FIGURE 10.4 Texaco Controlled Combustion System.

Source: Reference 73

of fuel injected is immediately swept by the swirling air into the spark plug region where ignition occurs and a flame front is established. The continuing stream of injected fuel mixes with swirling air and is swept into the flame region. In many respects, the Texaco process resembles the spray burning typical of diesel combustion with the difference that ignition is achieved by energy from an electric spark rather than by high compression temperatures. The Texaco engine, like the diesel engine, does not have a significant fuel octane requirement. Further, use of positive spark ignition obviates fuel cetane requirements characteristic of diesel engines. The resultant flexibility of the TCCS engine regarding fuel requirements is a significant attribute.

In contrast to the TCCS system, Ford's PROCO system employs relatively early injection, vaporization, and mixing of fuel with air. The combustion process more closely resembles the premixed flame propagation typical of conventional gasoline engines. The PROCO engine, therefore, has a definite fuel octane requirements and cannot be considered a multifuel system.

The TCCS engine operates with high compression ratios and with little or no inlet air throttling except at idle conditions. As a consequence, fuel economy is excellent--both at full load and under part-load operating conditions.

(2) Exhaust emissions and fuel economy -- Low exhaust temperatures characteristic of the TCCS system have necessitated use of exhaust oxidation catalysts for control of HC emissions to low levels. All recent development programs have, therefore, included use of exhaust oxidation catalysts, and most of the data reported here represent tests with catalysts installed or with engines tuned for use with catalysts.

Figures 10-5 and 10-6 present fuel economy data at several exhaust emissions levels for two vehicles--a U.S. Army M-151

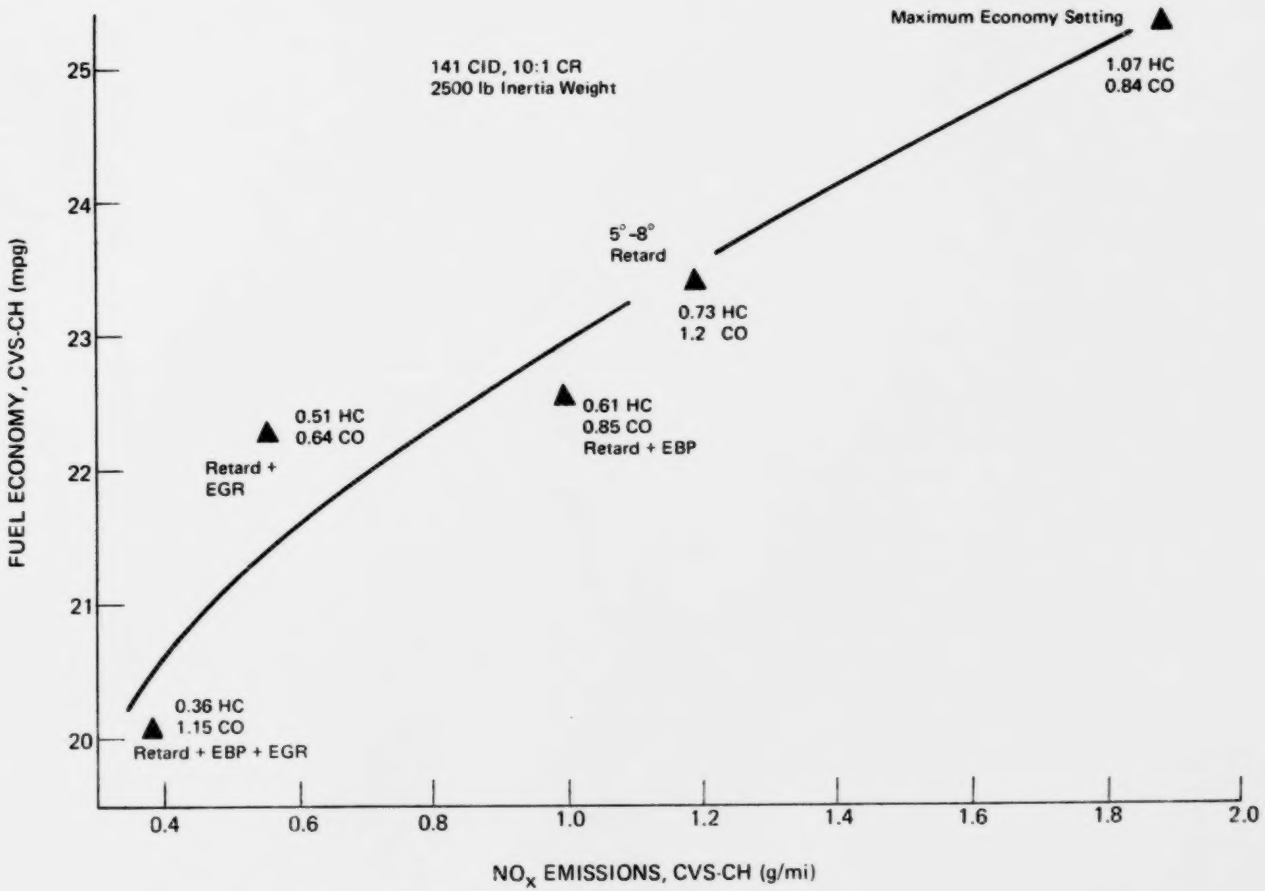


FIGURE 10.5 Texaco TCCS Powered Cricket Vehicle.

Source: Reference 73

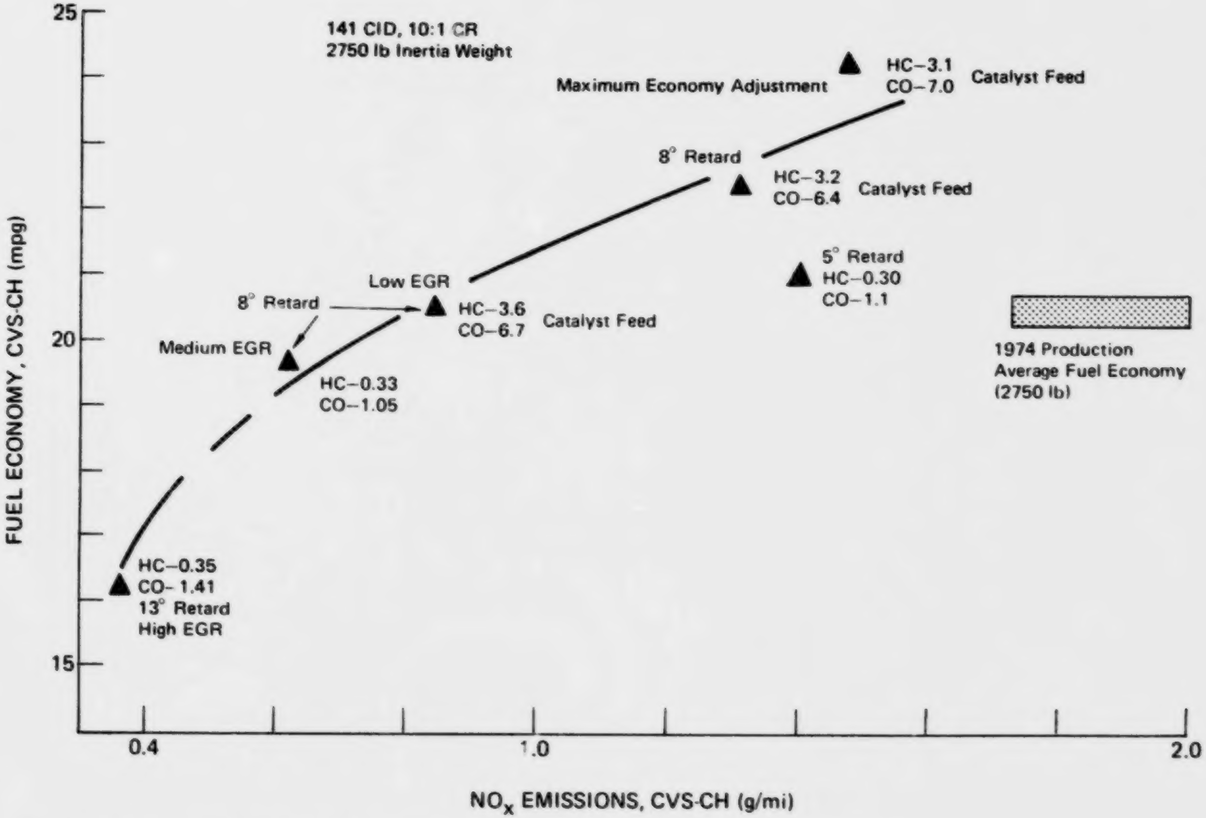


FIGURE 10.6 Turbocharged Texaco TCCS, M151 Vehicle.

Source: Reference 73

vehicle with naturally aspirated 4-cylinder TCCS conversion, and a Plymouth Cricket with turbocharged 4-cylinder TCCS engine.[73,74] Turbocharging has been used to advantage to increase maximum power output. Also plotted in these figures are average fuel economies for 1974 production vehicles of similar weight.[72]

When optimized for maximum fuel economy, the TCCS vehicles can meet NO_x levels of about 2.0 g/mi. It should be noted that these are relatively lightweight vehicles and that increasing vehicle weight to the 4,000-5,000-pound level could result in significantly increased NO_x emissions. Figures 10-5 and 10-6 both show that engine modifications for reduced NO_x levels including retarded combustion timing, EGR and increased exhaust back pressure result in substantial fuel economy penalties.

For the naturally aspirated engine, reducing NO_x emissions from the 2.0 g/mi level to 0.4 g/mi incurred a fuel economy penalty of 20%. Reducing NO_x from the turbocharged engine from 1.5 g/mi to 0.4 g/mi gave a 25% fuel economy penalty. Fuel economies for both engines appear to decrease uniformly as NO_x emissions are lowered.

For the current TCCS systems, most of the fuel economy penalty associated with emissions control can be ascribed to control of NO_x emissions, although several of the measures used for NO_x control (retarded combustion timing and increased exhaust back pressure) also help to reduce HC emissions. HC and CO emissions are effectively controlled with oxidation catalysts resulting in relatively minor reductions in engine efficiency.

(3) TCCS fuel requirements -- The TCCS engine is unique among stratified-charge systems in its multifuel capability. Successful operation with a number of fuels ranging from gasoline to No. 2 diesel has been demonstrated. Table 10-1 lists emissions levels and fuel economies obtained with a turbocharged TCCS-powered

M-151 vehicle when operated on each of four different fuels.[74] These fuel encompass wide ranges in gravity, volatility, octane number and cetane level as shown in Table 10-2.

TABLE 10-1

Emissions and Fuel Economy of Turbocharged TCCS Engine-Powered Vehicle[1]

Fuel	Emissions g/mi[2] HC	CO	NO_x	Fuel Economy mpg[2]
Gasoline	0.33	1.04	0.61	19.7
JP-4	0.26	1.09	0.50	20.2
100-600	0.14	0.72	0.59	21.3
No. 2 Diesel	0.27	1.14	0.60	23.0

[1] M-151 vehicle, 8 degrees combustion retard, 16% light load EGR, two catalysts.

[2] CVS-CH, 2,750 pounds inertia weight.

REF. 74

TABLE 10-2

Fuel Specifications for TCCS Emission Tests

	Gasoline	100-600	JP-4	No. 2 Diesel
Gravity, °API	58.8	48.6	54.1	36.9
Sulfur, %	-	0.12	0.020	0.065
Distillation, °F				
IBP	86	110	136	390
10%	124	170	230	435
50%	233	358	314	508
90%	342	544	459	562
EP	388	615	505	594
TEL, g/gal.	0.002	0.002	-	-
Research Octane	91.2	57	-	-
Cetane No.	-	35.6	-	48.9 REF. 74

Generally, the emissions levels were little affected by the wide variations in fuel properties. Vehicle fuel economy varied in proportion to fuel energy content.

As stated above, the TCCS engine is unique in its multifuel capability. The results of Tables 10-1 and 10-2 demonstrate that the engine has neither significant fuel octane nor cetane requirements and, further, that it can tolerate wide variations in fuel volatility. The flexibility offered by this type of system could be of major importance in future years.

(4) Durability, performance, production readiness -- Emissions-control-system durability has been demonstrated by mileage accumulation tests. Ignition-system service is more severe than for conventional engines due to heterogeneity of the F/A mixture and also to the high compression ratios involved. The ignition system has been the subject of intensive development and significant progress in system reliability has been made.

A preproduction, prototype engine employing the TCCS process is now being developed by the Hercules Division of White Motors Corporation, under contract to the U.S. Army Tank Automotive Command. Southwest Research Institute will conduct reliability tests on the White-developed engines when installed in military vehicles.

10.3 Small Volume Prechamber Engines (3-Valve Prechamber Engines, Jet Ignition Engines, Torch Ignition Engines)

a. General -- A number of designs achieve charge stratification through division of the combustion region into two adjacent chambers. The emissions reduction potential for two types of dual-chamber engines has been demonstrated. First, in a design traditionally called the "prechamber engine," a small auxiliary or ignition chamber equipped with a spark plug communicates with the much larger main combustion chamber located in the space above the piston (Figure 10-7). The prechamber, which typically contains 5%-15% of the total combustion volume, is supplied with a small quantity of fuel-rich ignitable F/A mixture while a large quantity of very lean and normally unignitable mixture is applied to the main chamber above the piston. Expansion of high-temperature flame products from the prechamber leads to ignition and burning of the lean main chamber F/A charge. Ignition and combustion in the lean, main-chamber region are promoted both by the high temperatures of prechamber gases and by

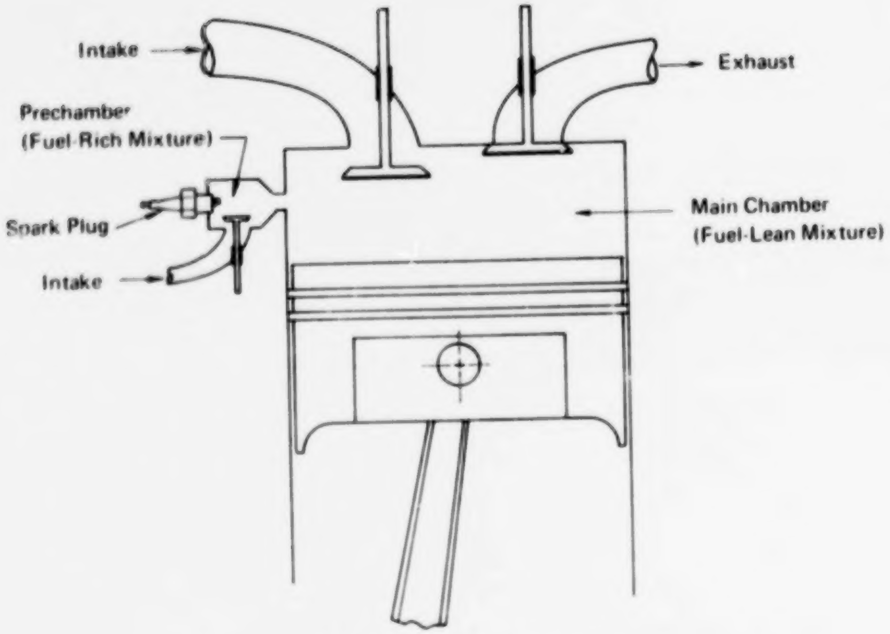

Intake
Exhaust
Prechamber
(Fuel-Rich Mixture)
Main Chamber
(Fuel-Lean Mixture)
Spark Plug
Intake

FIGURE 10.7 3-Valve Prechamber Engine Concept.

the mixing that accompanies the jet-like motion of prechamber products into the main chamber.

Operation with lean overall mixtures tend to limit peak combustion temperatures, thus minimizing the formation of nitric oxide. Further, lean-mixture combustion products contain sufficient oxygen for complete oxidation of HC and CO in the engine cylinder and exhaust system.

It should be reemphasized here that a traditional problem with lean mixture engines has been low exhaust temperatures which tend to quench HC oxidation reactions leading to excessive emissions.

Control of HC emissions to low levels requires a retarded or slowly developing combustion process. The consequent extension of heat release into late portions of the engine cycle tends to raise exhaust gas temperatures, thus promoting complete oxidation of HC and CO.

b. Historical background and current status

(1) Early development objectives and engine designs -- The prechamber, stratified-charge engine has existed in various forms for many years. Early work by Ricardo[65] indicated that the engine could perform very efficiently within a limited range of carefully controlled operating conditions. Both fuel-injected and carbureted prechamber engines have been built. A fuel-injected design initially conceived by Brodersen[75] was the subject of extensive study at the University of Rochester for nearly a decade.[76,77] Unfortunately, the University of Rochester work was undertaken prior to widespread recognition of the automobile emissions problem, and, as a consequence, emissions characteristics of the Brodersen engine were not determined. Another prechamber engine receiving attention in the early 1960's is that conceived by R. M. Heintz.[78] The objectives of this design were reduced HC emissions, increased

fuel economy and more flexible fuel requirements.

Experiments with a prechamber engine design called "the torch-ignition engine" were reported in the U.S.S.R. by Nilov[79] and later by Kerimov and Mekhtier.[80] This designation refers to the torch-like jet of hot combustion gases issuing from the precombustion chamber upon ignition. In a recent publication,[81] Varshaoski _et_ _al_. have presented emissions data obtained with a torch-ignition engine. These data show significant pollutant reductions relative to conventional engines; however, their interpretation in terms of requirements based on the U.S. emissions test procedure is not clear.

(2) Current developments -- A carbureted three-valve, prechamber engine, the Honda CVCC system, has received considerable recent attention as a potential low-emissions power plant.[82] This system is illustrated in Figure 10-8. Honda's current design employs a conventional engine block and piston assembly. Only the cylinder head and fuel inlet system differ from current automotive practice. Each cylinder is equipped with a small precombustion chamber communicating by means of an orifice with the main combustion chamber situated above the piston. A small inlet valve is located in each prechamber. Larger inlet and exhaust valves typical of conventional automotive practice are located in the main combustion chamber. Proper proportioning of F/A mixture between prechamber and main chamber is achieved by a combination of throttle control and appropriate inlet valve timing. A relatively slow and uniform burning process giving rise to elevated combustion temperatures late in the expansion stroke and during the exhaust process is achieved. High temperatures in this part of the engine cycle are necessary to promote complete oxidation of HC and CO. It should be noted that these elevated exhaust temperatures are necessarily obtained at the expense of a fuel economy penalty.

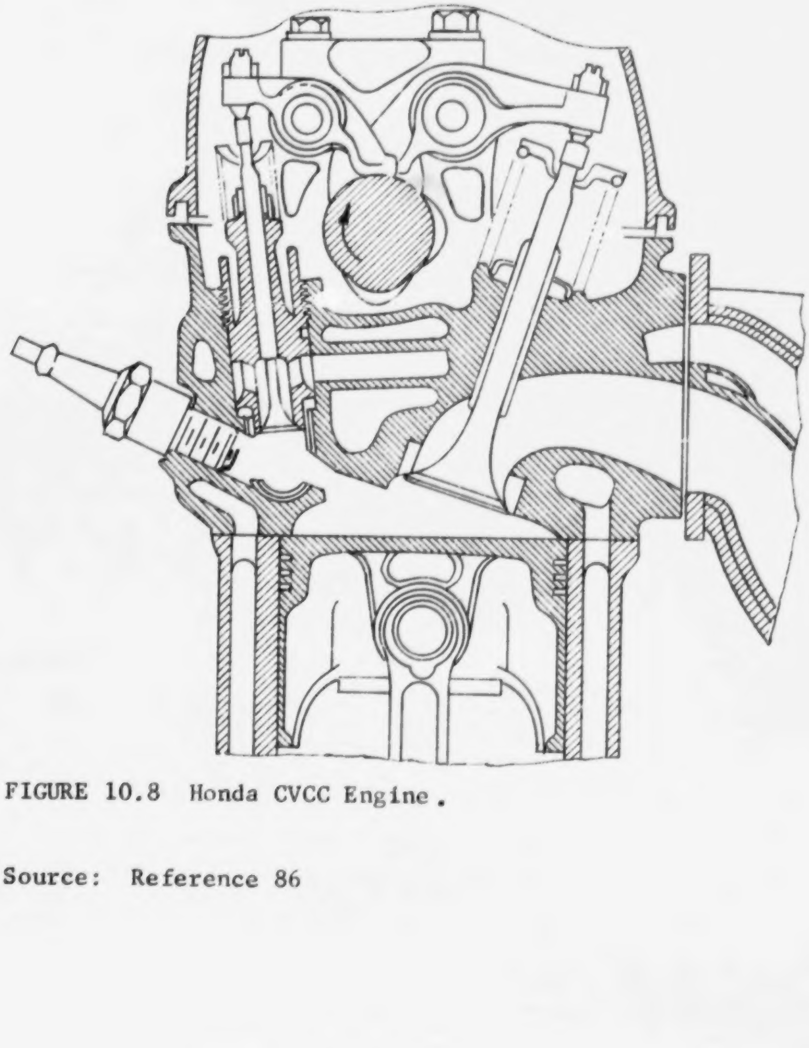


FIGURE 10.8 Honda CVCC Engine.

Source: Reference 86

To reduce HC and CO emissions to required levels, it has been necessary for Honda to employ specially designed inlet and exhaust systems. Supply of extremely rich F/A mixtures to the precombustion chambers requires extensive inlet manifold heating to provide adequate fuel vaporization. This is accomplished with a heat exchange system between inlet and exhaust streams.

To promote maximum oxidation of HC and CO in the lean mixture CVCC engine exhaust gases, it has been necessary to conserve as much exhaust heat as possible and also to increase exhaust manifold residence time. This has been done by using a relatively large exhaust manifold fitted with an internal heat shield or liner to minimize heat losses. In addition, the exhaust ports are equipped with thin metallic liners to minimize loss of heat from exhaust gases to the cylinder heat casting.

Engines similar in concept to the Honda CVCC system are under development by other companies including Toyota and Nissan in Japan and General Motors and Ford in the United States.

Honda presently markets a CVCC-powered vehicle in Japan and plans U.S. introduction in 1975. Other manufacturers, including General Motors and Ford in the U.S., hafe stated that CVCC-type engines could be manufactured for use in limited numbers of vehicles by as early as 1977 or 1978.

c. Emissions and fuel economy with CVCC-type engines

(1) Recent emissions test results -- Results of emissions tests with the Honda engine have been very promising. The emissions levels shown in Table 10-3 are typical and demonstrate that the Honda engine can meet statutory HC and CO standards and can approach the statutory NO_x standard.[83] Of particular importance, durability of this system appears excellent as evidenced by the high mileage emissions levels reported in Table 10-3. Any deterioration of

emissions after 50,000 miles of engine operation was slight and apparently insignificant.

TABLE 10-3

Honda Compound Vortex-Controlled Combustion-Powered Vehicle[1] Emissions

	Emissions,[2] g/mi			Fuel Economy, mpg	
	HC	CO	NO_x	1975 FTP	1972 FTP
Low Mileage Car[3] No. 3652	0.18	2.12	0.89	22.1	21.0
50,000-Mile Car[4] No. 2034	0.24	1.75	0.65	21.3	19.8
1976 Standards	0.41	3.4	2.0	-	-
1977 Standards	0.41	3.4	0.4	-	-

---

[1] Honda Civic vehicles.

[2] 1975 CVS-CH procedure with 2000-lb inertia weight.

[3] Average of five tests.

[4] Average of four tests.

REF. 83

Recently, the EPA has tested a larger vehicle converted to the Honda system.[84] This vehicle, a 1973 Chevrolet Impala with a 300-CID V-8 engine, was equipped with cylinder heads and an induction system built by Honda. The vehicle met the 1976 interim federal emissions standards though NO_x levels were substantially higher than for the much lighter-weight Honda Civic vehicles.

Results of development tests conducted by General Motors are shown in Table 10-4.[85] These tests involved a 5,000 lb Chevrolet Impala with stratified-charge engine conversion. HC and CO emissions were below 1977 statutory limits, while NO_x emissions ranged from 1.5 to 2.0 g/mi. Average CVS-CH fuel economy was 11.2 miles per gallon.

TABLE 10-4

Emissions and Fuel Economy for Chevrolet Impala Stratified-Charge Engine Conversion

Test	Exhaust Emissions, g/mi[1]			Fuel Economy, mpg
	HC	CO	NO_x	
1	0.20	2.5	1.7	10.8
2	0.26	2.9	1.5	11.7
3	0.20	3.1	1.9	11.4
4	0.29	3.2	1.6	10.9
5	0.18	2.8	1.9	11.1
Average	0.23	2.9	1.7	11.2

---

[1] CVS-CH, 5,000-lb inertia weight.

REF. 85

(2) HC control has a significant impact on fuel economy -- In Figure 10-9, fuel economy data for several levels of HC emissions from CVCC-type stratified-charge engines are plotted.[86,87] At the 1.0 g/mi HC level, stratified-charge engine fuel economy appears

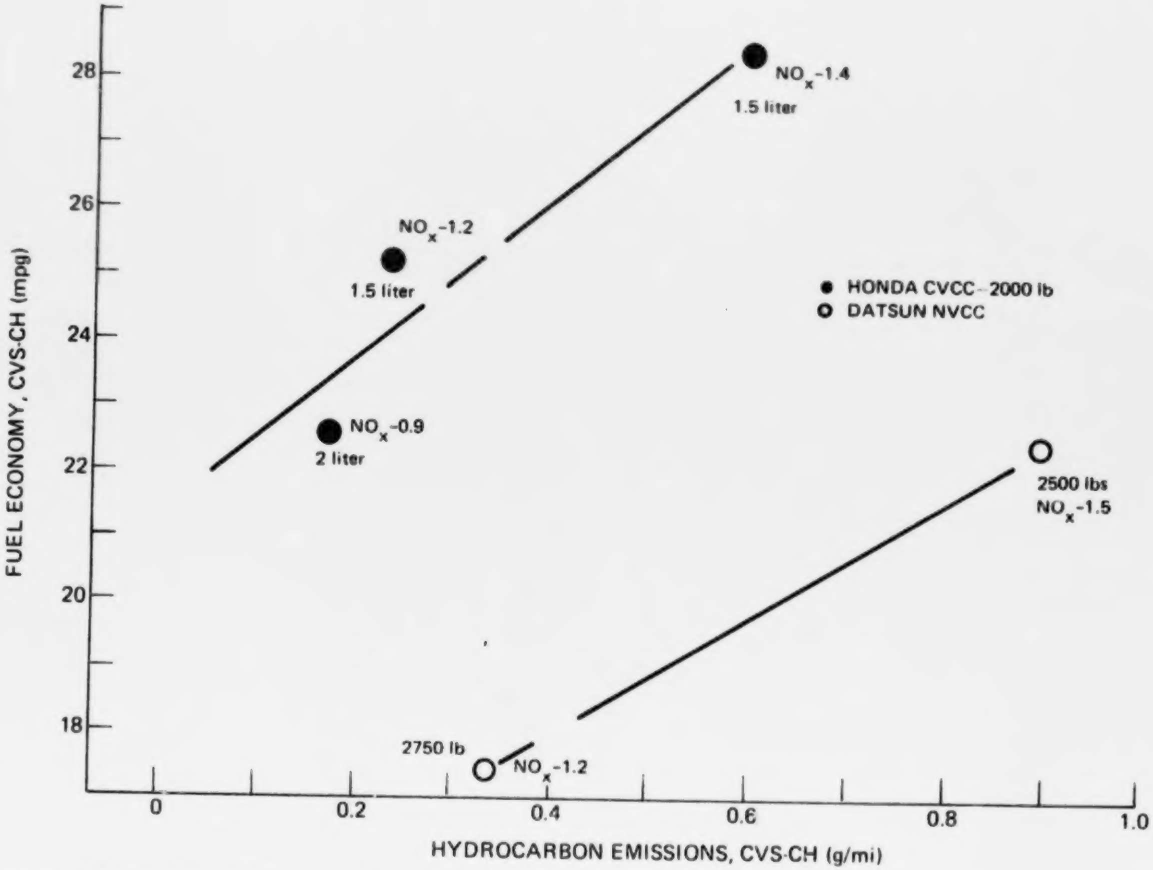


FIGURE 10.9 Fuel Economy Versus HC Emissions for 3-Valve Prechamber Engines.

Source: `References 86, 87

better than the average fuel economy for 1973-74 production vehicles of equivalent weight. Reduction of HC emissions below the 1.0 g/mi level necessitates lowered compression ratios and/or retarded ignition timing with a consequent loss of efficiency. For the lightweight (2,000-lb) vehicles, the 0.4 g/mi HC emissions standard can be met with a fuel economy of 25 mpg, a level approximately equal to the average of 1973 production vehicles in this weight class.[72] For heavier cars, the HC emissions versus fuel economy trade-off appears less favorable. A fuel economy penalty of 10% relative to 1974 production vehicles in the 2,750-lb weight class is required to meet the statutory 0.4 g/mi HC level.

(3) Effect of NO_x emissions control on fuel economy -- Data showing the effect of NO_x emissions control appear in Figure 10-10.[86] These data are based on modifications of a Honda CVCC-powered Civic vehicle (2,000-lb test weight) to meet increasingly stringent NO_x standards ranging from 1.2 g/mi to as low as 0.3 g/mi. For all tests, HC and CO emissions are within the statutory 1977 standards.

NO_x control as shown in Figure 10-10 has been effected by use of EGR in combination with retarded ignition timing. It is clear that control of NO_x emissions to levels below 1.0 to 1.5 g/mi results in significant fuel economy penalties. The penalty increases uniformly as NO_x emissions are reduced and appears to be 25% or more as the 0.4 g/mi NO_x level is approached.

It should be emphasized that the data of Figure 10-10 apply specifically to a 2,000-lb vehicle. With increased vehicle weight, NO_x emissions control becomes more difficult and the fuel economy penalty more severe. The effect of vehicle weight on NO_x emissions is apparent when comparing the data of Table 10-3 for 2,000-lb vehicles with that of Table 10-4 for a 5,000-lb vehicle. While HC and CO emissions for the two vehicles are roughtly comparable, there is over a factor of two difference in average NO_x emissions.

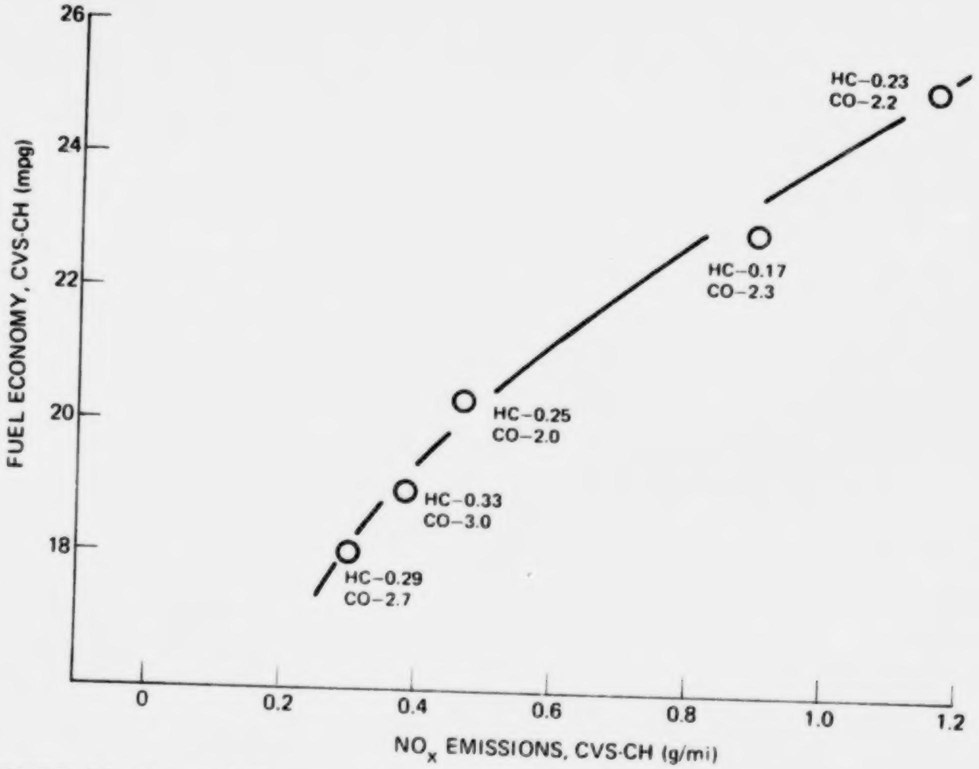


FIGURE 10.10 Fuel Economy Versus NO_x Emissions for Honda CVCC Powered Vehicles.

Source: Reference 86

d. Fuel requirements -- To meet present and future U.S. emissions-control standards, compression ratio and maximum ignition advance are limited by HC emissions control rather than by the octane quality of existing gasolines. CVCC engines tuned to meet 1975 California emissions standards appear to be easily satisfied with presently available 91 RON commercial unleaded gasolines.

CVCC engines are lead-tolerant and have completed emissions certification test programs using leaded gasolines. However, with the low octane requirement of the CVCC engine as noted above, the economic benefits of lead antiknock compounds are not realized.

It is possible that fuel volatility characteristics may be of importance in relation to vaporization within the high-temperature, fuel-rich regions of the prechamber cup, inlet port and prechamber inlet manifold. However, experimental data on this question do not appear to be available at present.

10.4 Divided-Chamber Staged Combustion Engines (Large-Volume Prechamber Engines, Fuel-Injected Blind Prechamber Engines)

a. General -- Dual-chamber engines of a type often called "divided-chamber" or "large-volume prechamber" employ a two-stage combustion process. Here initial rich-mixture combustion and heat release (first stage of combustion) are followed by rapid dilution of combustion products with relatively low-temperature air (second state of combustion). The object of this engine design is to effect the transition from overall rich combustion products to overall lean products with sufficient speed that time is not available for formation of significant quantities of NO. During the second low-temperature, lean stage of combustion, oxidation of HC and CO goes to completion.

An experimental divided-chamber engine design that has been built and tested is represented schematically in Figure 10-11.[87,88] A dividing orifice (3) separates the primary combustion chamber (1) from the secondary combustion chamber (2), which includes the cylinder volume above the piston top. A fuel injection (4) supplies fuel to the primary chamber only.

Injection timing is arranged such that fuel continuously mixes with air entering the primary chamber during the compression stroke. At the end of compression, as the piston nears its top center position, the primary chamber contains an ignitable F/A mixture while the secondary chamber adjacent to the piston top contains only air. Following ignition of the primary chamber mixture by a spark plug (6) located near the dividing orifice, high-temperature, rich-mixture combustion products expand rapidly into and mix with the relatively cool air contained in the secondary chamber. The resulting dilution of combustion products with attendant temperature reduction rapidly suppresses formation of NO. At the same time, the presence of excess air in the secondary chamber tends to promote complete oxidation of HC and CO.

b. Exhaust emissions and fuel economy -- Results of limited research conducted both by university and industrial laboratories indicate that NO_x reductions of as much as 80%-95% relative to conventional engines are possible with the divided-chamber staged combustion process. Typical experimentally determined NO_x emissions levels are presented in Figure 10-12.[89] Here NO_x emissions for two different divided-chamber configurations are compared with typical emissions levels for conventional uncontrolled automobile engines. The volume ratio, β appearing as a parameter in Figure 10-12, represents the fraction of total combustion volume contained in the primary chamber. For β values approaching 0.5 or lower, NO_x emissions reach extremely low levels. However, maximum power output capability for a given engine size decreases with decreasing β values.

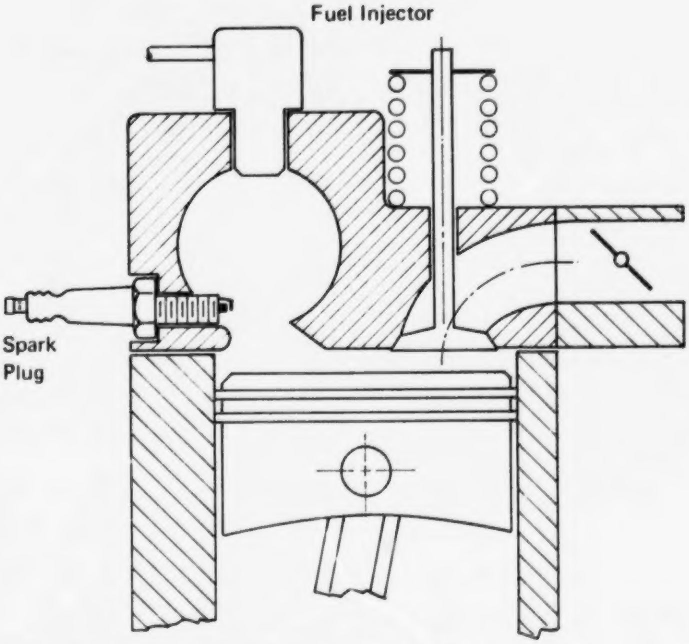

Fuel Injector
Spark
Plug

FIGURE 10.11 Ford Divided Chamber.

Source: References 87, 88

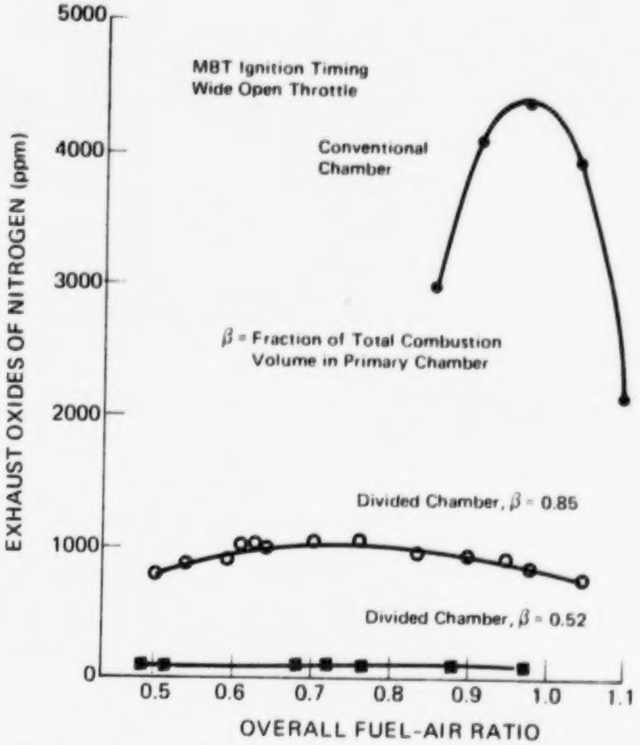


FIGURE 10.12 Comparison of Conventional and Divided Combustion Chamber NO_x Emissions.

Source: Reference 90

Optimum primary chamber volume must ultimately represent a compromise between low emissions levels and desired maximum power output.

HC, and particularly CO, emissions from the divided-chamber engine are substantially lower than conventional engine levels. However, further detailed work with combustion-chamber geometries and fuel-injection systems will be necessary to fully evaluate the potential for reduction of these emissions.

Recent tests by Ford Motor Company show that the large volume prechamber engine may be capable of better HC emissions control and fuel economy than their PROCO engine. This is shown by the laboratory engine test comparison of Table 10-5.[83]

TABLE 10-5

Single-Cylinder Low Emissions Engine Tests

Engine	NO_x Reduction Method	Emissions, g/l. hp-hr NO_x	Emissions, g/l. hp-hr HC	Emissions, g/l. hp-hr CO	Fuel Economy, lb/l. hp-hr
PROCO	EGR	1.0	3.0	13.0	0.377
Divided Chamber	None	1.0	0.4	2.5	0.378
PROCO	EGR	0.5	4.0	14.0	0.383
Divided Chamber	None	0.5	0.75	3.3	0.377

REF. 83

Fuel-injection-spray characteristics are critical to the control of HC emissions from this type of engine, and Ford's success in this regard is probably due in part to use of the already highly developed PROCO gasoline injection system. Figure 10-13 is a cutaway view of Ford's adaptation of a 400-CID V-8 engine to the divided-chamber system.[90]

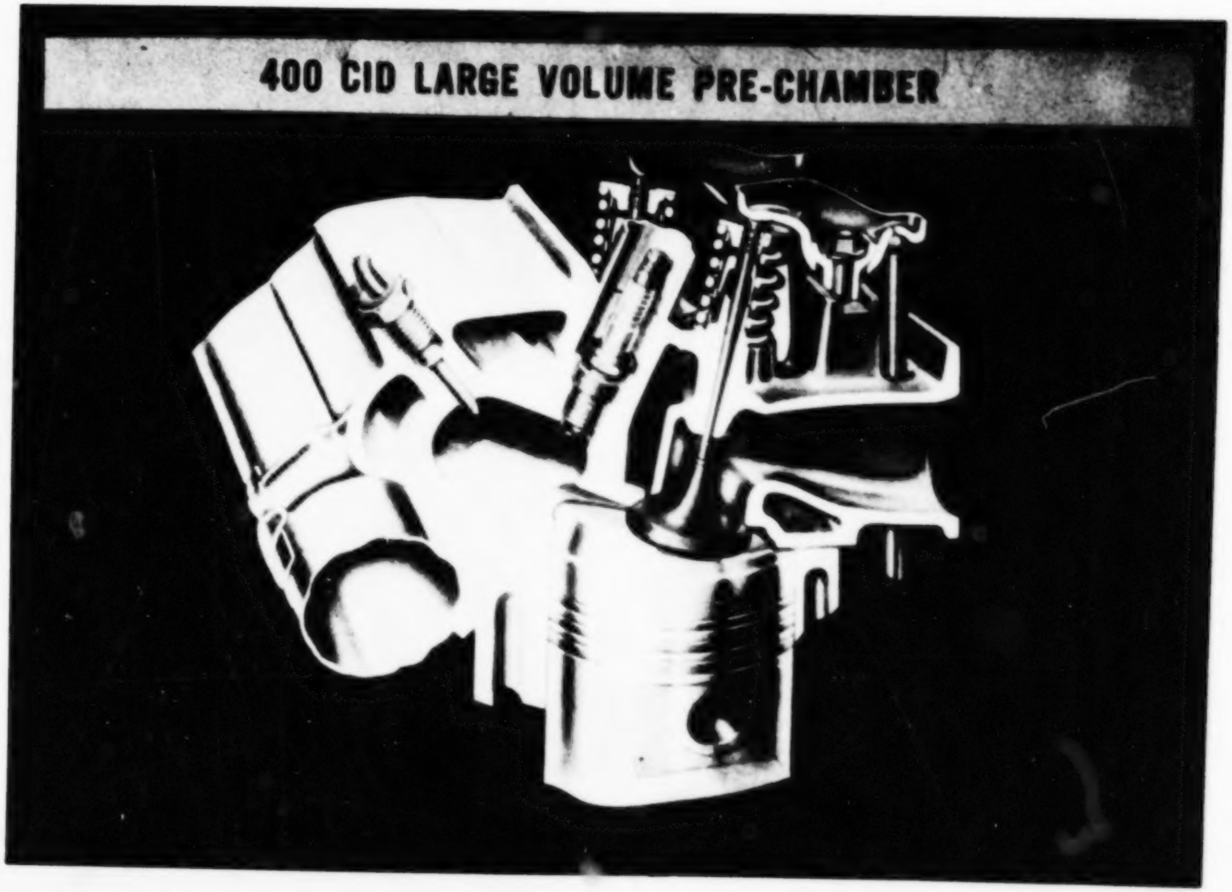

400 CID LARGE VOLUME PRE-CHAMBER

FIGURE 10.13

Source: Reference 90

Volkswagen (VW) has recently published results of a program aimed at development of a large-volume prechamber engine.[91] In the VW adaptation, the primary chamber which comprises about 30% of the total clearance volume is fueled by a direct, time injection system, and auxiliary fuel for high-power output conditions is supplied to the cylinder region by a carburetor.

Table 10- 6 presents emissions data for both air-cooled and water-cooled versions of VW's divided-chamber engine.[92] Emissions levels, while quite low, do not meet the ultimate 1978 statutory U.S. standards.

TABLE 10-6

Volkswagen Large-Volume Prechamber Engine Emissions

	Exhaust Emissions, g/mi[1]			
Engine	HC	CO	NO_x	Engine Specifications
1.6 Liter Air-Cooled	2.0	5.0	0.9	8.4:1 compression ratio, prechamber 28% of total clearance volume, conventional exhaust manifold, direct prechamber fuel injection
2.0-Liter Water-Cooled	1.0	4.0	1.0	9:1 compression ratio, prechamber volume 28% of total clearance volume, simple exhaust manifold reactor, direct prechamber fuel injection

---

[1] CVS -CH

REF. 92

c. Problem Areas

A number of major problems inherent in the large volume prechamber engine remain to be solved. These problems include the following:

- Fuel injection spray characteristics are critically important to achieving acceptable HC emissions. The feasibility of producing a satisfactory injection system has not been established.
- Combustion noise due to high turbulence levels and, hence, high rates of heat release and pressure rise in the prechamber, can be excessive. It has been shown that the noise level can be modified through careful chamber design and combustion event timing.
- If the engine is operated with prechamber fuel injection as the sole fuel source, maximum engine power output is limited. This might be overcome by auxiliary carburetion of the air inlet for maximum power demand or possibly by turbocharging. Either approach adds to system complexity.
- The engine is characterized by low exhaust temperatures typical of most lean mixture engines.

11. DIESEL ENGINES

11.1 Introduction

Many techniques have been sought for reducing the harmful emissions from passenger cars in an effort to clean the air. Exhaust-emissions standards have been set by the federal government and the state of California for three species: hydrocarbon (HC), carbon monoxide (CO) and nitrogen oxides (NO_x). It is expected that other species which are equally or even more harmful than these will be controlled in the future.

The regulated and nonregulated emissions from diesel-powered cars are studied in this Section. The fuel economy and initial and maintenance costs of the diesel are compared with the gasoline engine. Finally, the intrinsic problem areas associated with the auto-ignition process in the diesel engine are examined.

The approach taken in this Section is to compare the characteristics of the diesel-powered cars with those of cars powered by regular gasoline engines, stratified-charge engines, Wankel, or gas turbine engines.

11.2 Regulated Emissions

a. General -- Table 11.1[93] and Figure 11.1 give a summary of tests carried out by EPA-Ann Arbor, and recent results obtained from the manufacturers. The Mercedes 220D and 240D and Datsun-Nissan 220C have an inertia weight of 3,500 lb, and the Peugeot 504D and Opel Rekord 2100D have an inertia weight (I.W.)of 3,000 lb. All of these engines have four cylinders. The hydrocarbon emission from the Peugeot 504D was 3.1 g/mi which is very high compared to all other diesel-powered cars. Recent results by Southwest Research[94] showed that the Peugeot 504D produced 2.0 g/mi HC. Peugeot Inc. reported at a meeting of foreign manufacturers held by the Committee on Motor Vehicles Emissions May 21-23, 1974, that with modifications, their

TABLE 11.1

Mass Emissions and Fuel Economy
From Diesel Engines
(1975 Federal Test Procedure)

Vehicle	No. of Tests	Inertia Weight	Transmission	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	Fuel Economy (mpg)
Mercedes 220D	5	3,500 lb	4 speed auto	0.34	1.42	1.43	23.6
Mercedes 220D (modified)	5	3,500 lb	4 speed auto	0.28	1.08	1.48	24.6
Mercedes 240D	3	3,500 lb	4 speed auto	0.18	1.0	1.5	23.6[1]
Peugeot 504D	5	3,000 lb	4 speed manual	3.11	3.42	1.07	25.2
Peugeot 504D (modified)	(Manufacturer's Data)	3,000 lb	4 speed manual	0.40-0.60	1.1-1.6	1.3-1.5	--
Datsun-Nissan 220C (as received)	2	3,500 lb	4 speed manual	0.38	1.69	1.72	24.0
Datsun-Nissan 220C (after 4,000 miles)	2	3,500 lb	4 speed manual	0.23	1.34	1.36	28.1
Opel Rekord 2100D	4	3,000 lb	3 speed auto	0.40	1.16	1.34	23.8
Pick-up Truck Retrofit (Nissan Diesel)	3	4,500 lb	4 speed manual	1.70	3.81	1.71	21.4

[1] The fuel economy in this case is based on one measurement only.

REF 93

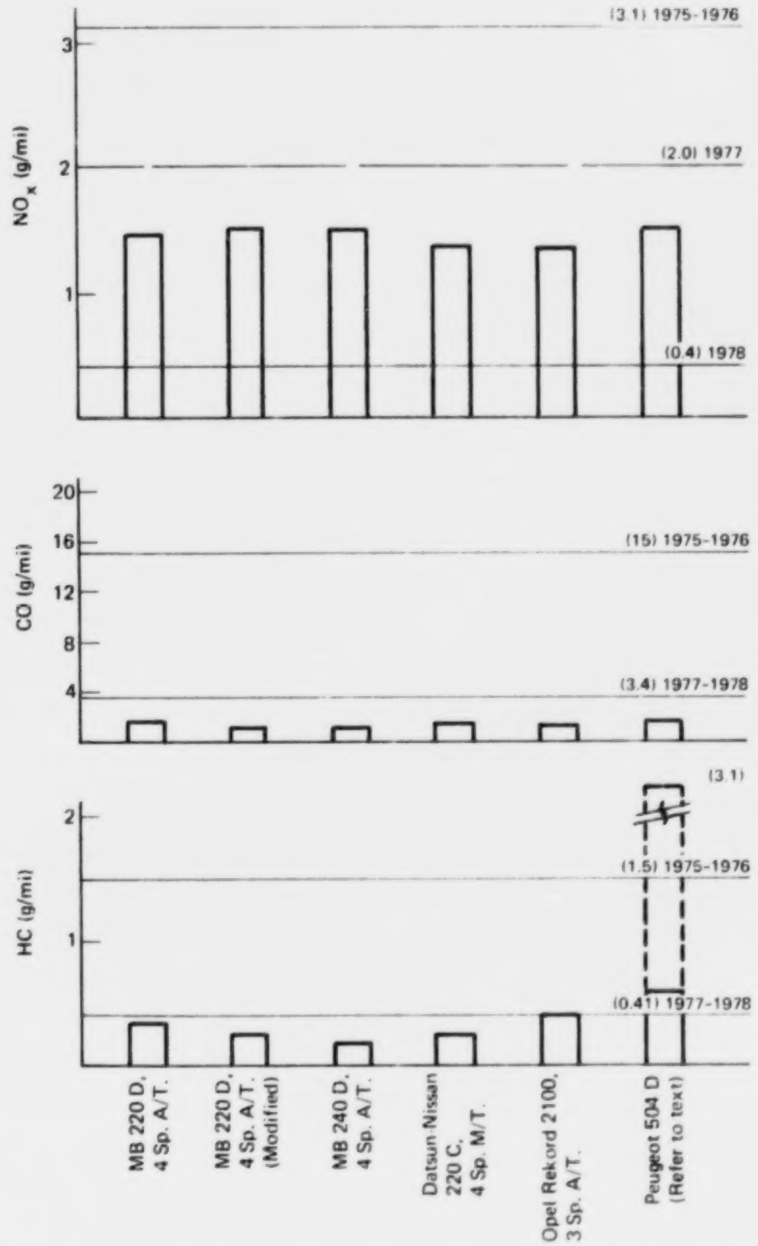


FIGURE 11.1 Emissions from Diesel Powered Cars (1975 FTP).

Source: Reference 94

car produces 0.6 g/mi HC.

Figure 11.1 shows that all of these diesel-powered cars, except the Peugeot 504D, can meet the 1975-76 Federal, 1975-76 California, and 1977 Nationwide Standards for HC, CO and NO_x. Also, all these cars, except the Peugeot 504D, can meet the 1978 Nationwide Standards for HC and CO. The problem with these diesel-powered cars is in meeting the NO_x emissions standard of 0.40 g/mi in 1978.

Some NO_x controls have been applied to the diesel engine and were found to affect the other emissions.

The control of NO_x emissions in diesel engines should be made during the combustion process. Whereas gasoline engines can employ a reduction catalyst[95,96] to control NO_x, such a technology is not effective in diesel engines because of the low level of CO, and the presence of a relatively high concentration of oxygen in the exhaust, even under full-load conditions.

Reduction in NO_x formation during the combustion process is achieved by reducing either the maximum temperature reached, the oxygen concentration, or the residence time.[97] This can be achieved by any of the following methods or a combination of them.

b. Exhaust gas recirculation -- EGR (exhaust gas recirculation) is an effective method for the reduction of NO_x emissions in diesel as well as in many other types of combustion engines. It is believed that its main effect is to reduce the maximum temperatures by increasing the heat capacity of the charge.

Data reported by Daimler-Benz AG [98] are given in Figure 11.2 for a speed of 2,400 rpm and two loads. Increasing EGR reduces NO_x with little effect on HC and CO up to EGR values of 20%, where NO_x is reduced by about 20% at the low load and 30% at the higher load. Increasing EGR above 20% results in an increase in HC and CO emissions. The smoke starts to increase at 40% EGR at the light load and 20% EGR

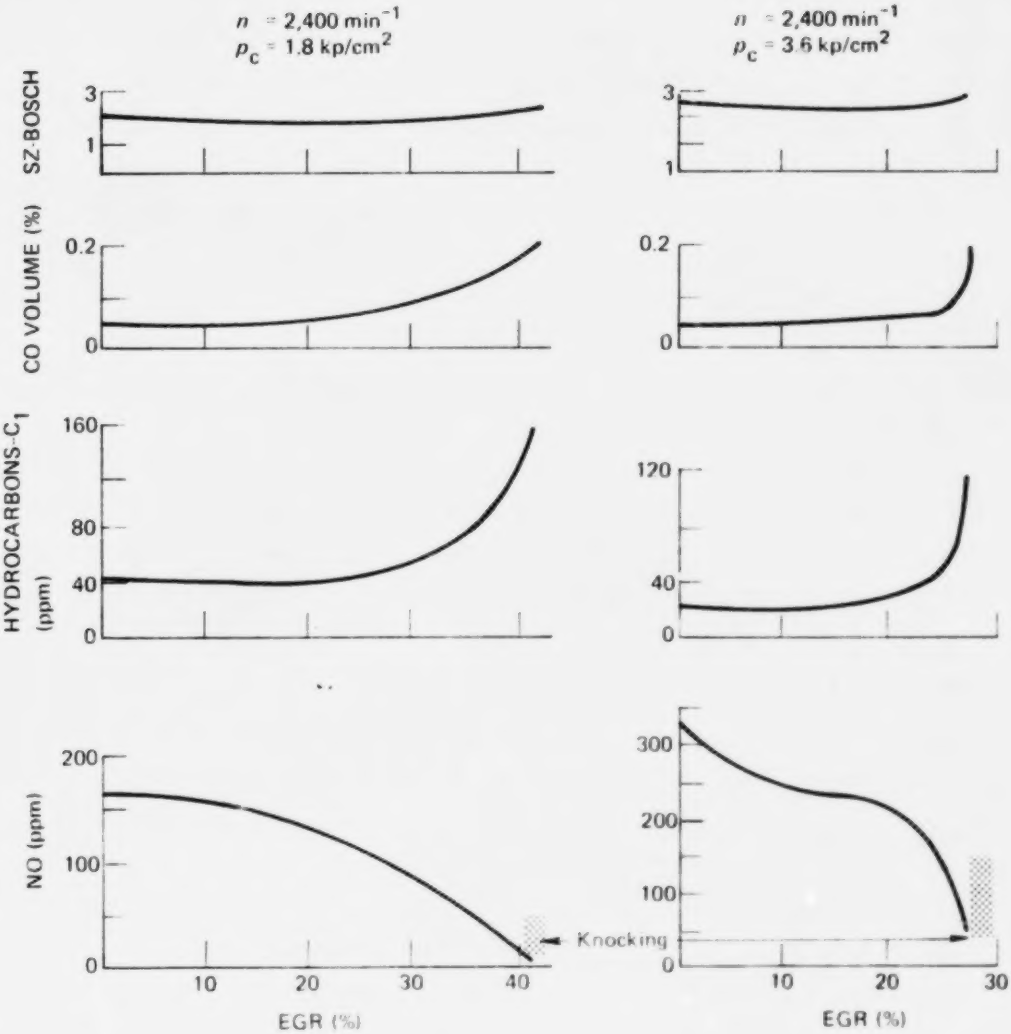


FIGURE 11.2 Effect of EGR on the Emissions from a Mercedes Diesel Engine.

Source: Reference 98

at the higher load. The Daimler-Benz results are for steady-state conditions.

The effects of EGR on the emissions under the 1975 Federal Test Procedure (FTP) are reported for an Opel Rekord diesel car,[99] and are shown in Figure 11.3. The increase in EGR increases both HC and CO emissions above the 1977 standards, while NO_x is still above the 1978 standards of 0.4 g/mi. From this figure, it appears that EGR is effective in reducing NO_x to about 1.0 g/mi, while the HC and CO emissions are below the 1977 and 1978 standards of 0.41 and 3.4 g/mi, respectively.

Daimler-Benz reported that EGR does not affect power or cause fuel penalty at part-load conditions. The effect of EGR on durability is still being investigated.

EGR can be achieved by recycling the exhaust gases from the exhaust to the inlet manifolds. Limited EGR is obtained by changing the valve overlap. The optimum percentage of EGR required to reduce NO_x varies with load. Efforts are being made to optimize the EGR at different loads to minimize the penalty in fuel economy and the emissions of HC, CO and smoke.

c. Injection timing -- Retarding the injection is an effective way to reduce the NO_x emissions because of its effect on maximum temperature and residence time. Retarding the timing also affects the HC and CO emissions. Results reported by Opel on the Opel Rekord diesel car, using the 1975 FTP are shown in Figure 11.4. By retarding the static injection from 6° BTDC (before top dead center) to 1.5° BTDC, NO_x emissions dropped by 30% (from 2.47 g/mi to 1.73 g/mi), while the HC and CO emissions increased by 44% and 33%, respectively.

Results obtained from Perkins,[100] given in Table 11.2, show the effect of retarding the injection timing by 4° with respect to the standard timing of 21° before top dead center.

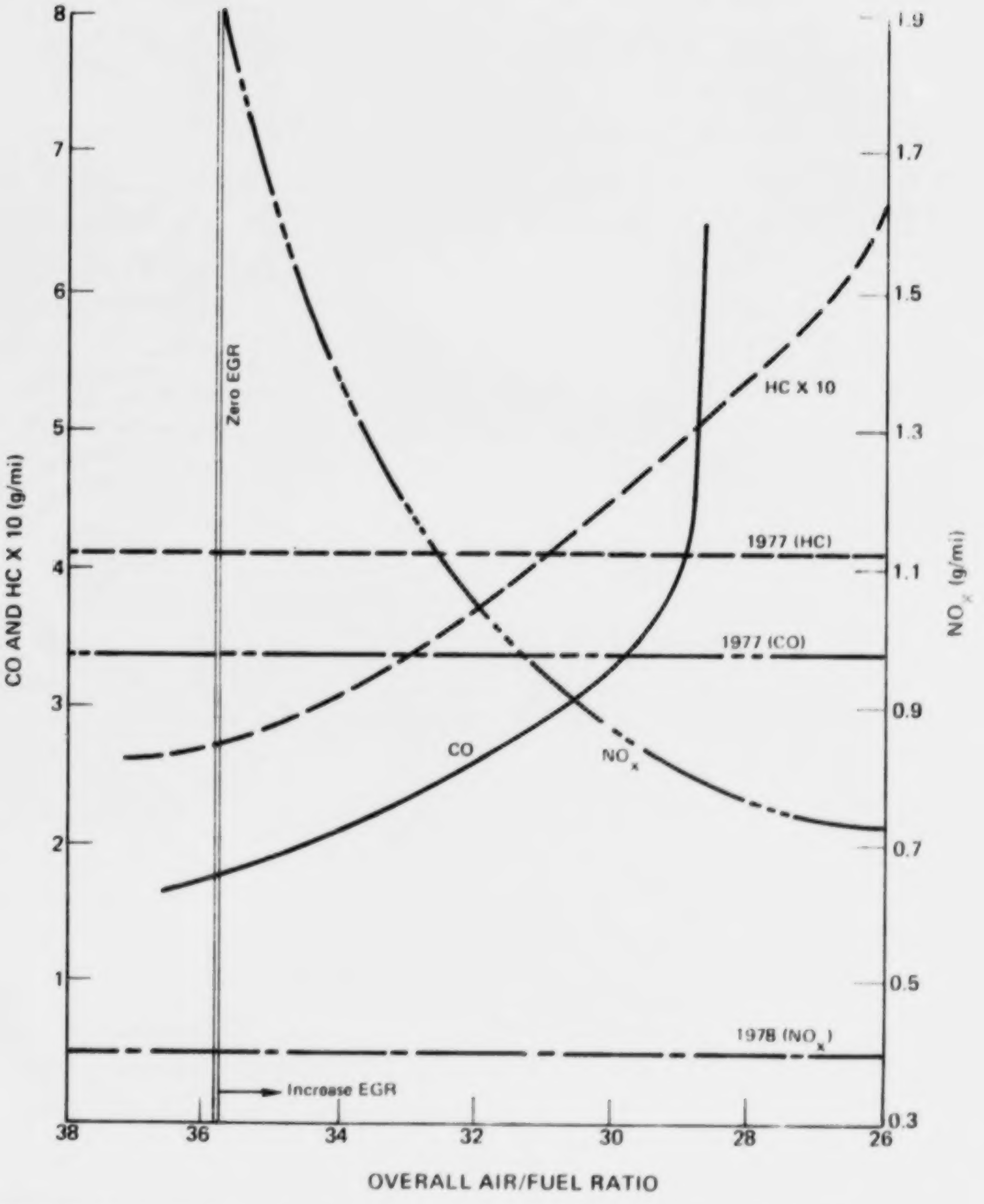


FIGURE 11.3 Effect of EGR on Opel Rekord Diesel Car (1975 FTP).

Source: Reference 99

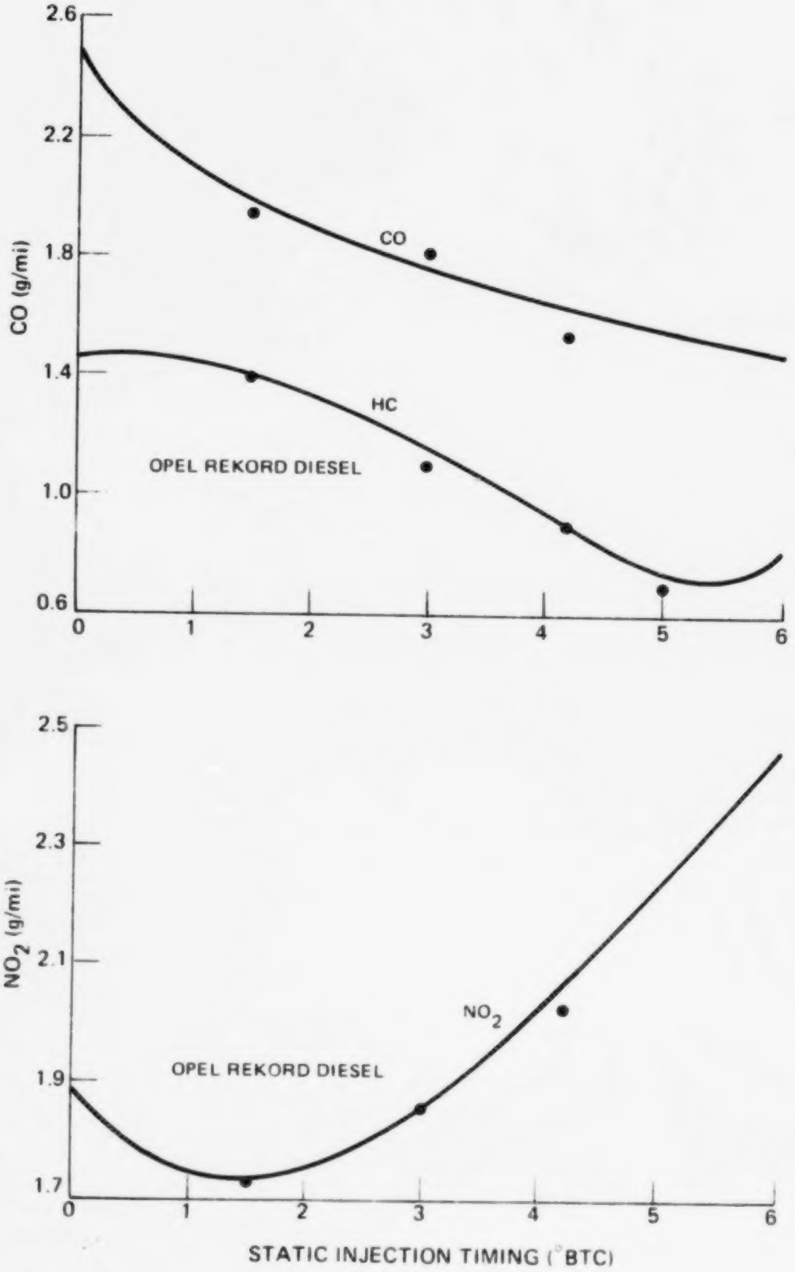


FIGURE 11.4

Source: Reference 99

TABLE 11.2

Effect of Injection Timing on Emissions from Perkins 154 Engine in Ford Zephyr Car (CVS Cycle)

	Standing Timing 21° BTCD g/mi	Retarded Timing 17° BTDC g/mi	% Change
HC	0.46	0.66	+ 43%
CO	2.79	3.78	+ 35%
NO_x	2.33	1.73	- 26%

REF. 100

Perkins reports that the change in fuel economy caused by this injection retard is within ±6% (which is their production tolerance), and that there has been no problem in meeting the smoke levels regulated by the European governments.

Retarding the injection is effective in reducing NO_x, but causes an increase in HC and CO. The 1978 emissions standards cannot be achieved by diesel-powered cars by using either injection retard or a combination of injection retard and EGR.

d. Other controls -- Other techniques used to reduce the NO_x emissions are control of the air/fuel ratio at light loads,[101] use of water injection,[97] use of fuel additives (Ref. 98 p. 749), use of low compression ratios together with supercharging, and modifications in the fuel-injection system and combustion-chamber design.

e. Summary -- In summary, the automotive diesel engine manufacturers are uncertain that they can meet the 0.40 g/mi standard for NO_x in the future, even in an experimental engine. They feel that the diesel engine can meet a level of NO_x = 1.5-2.0 g/mi with little changes in the design of current production engines, without any penalty in fuel economy. Ricardo and Co. Engineers, in a recent report to EPA,[102] indicated that a conventional, naturally aspirated swirl-chamber diesel engine, in a 3,500 lb vehicle, should be able to achieve HC = 0.41 g/mi, CO = 3.4 g/mi and NO_x = 1.5 g/mi. Some EGR may be necessary to ensure a sufficient margin for production tolerances.

It is anticipated that levels of NO_x equal to 1.0 g/mi, or even as low as 0.6 g/mi, might be reached in the future if sufficient research is made to optimize all the NO_x control techniques.

11.3 Nonregulated Emissions

The nonregulated emissions studies in this Section are: particulates, benzo (a) pyrine, sulfur dioxide, sulfuric acid, aldehydes and ammonia. Many of these nonregulated pollutants are as harmful or even more harmful than the three regulated species. It is expected that some of these undesirable species will be regulated in the future.

a. Particulates -- Particulates from diesel engines appear as blue and white smoke under cold-running conditions and low loads, and as black smoke near full-load operation. The blue and white smoke contains unburned and partially oxidized fuel, and the black smoke is mainly carbon.

Figure 11.5[93] shows the airborne particulate emissions in grams per mile on the 1975 FTP from three diesel powered cars, two American 1975 gasoline-powered cars, and a PROCO-Capri car. The two gasoline cars are equipped with catalytic converters. In one of the gasoline cars, the aged catalyst increased the particulate emissions by 267%. The PROCO-Capri car produced more particulates than the gasoline cars. The diesels produced the highest concentration of particulate emissions.

The proposed level of 0.1 g/mi over the constant-volume-sampling cycle during the federal testing procedure is difficult to achieve by the diesel engine. A proposed method to reduce particulate

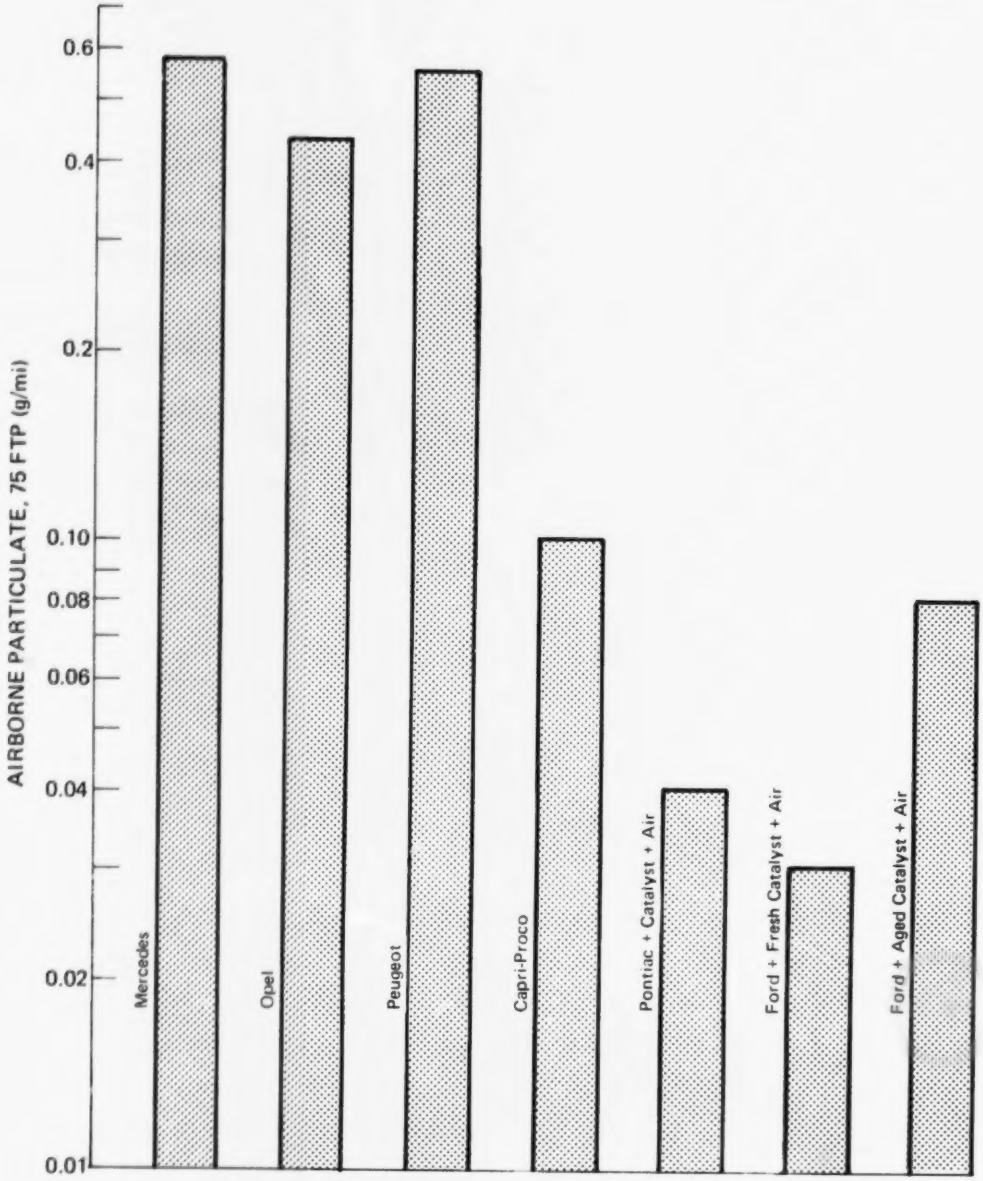


FIGURE 11.5 Airborne Particulates Emitted from Diesel and Gasoline Powered Cars.

Source: Reference 93

emissions is a soot filter (non-catalytic)[102] which would hold soot particles emitted at part loads and burn them at high loads when the exhaust temperatures are high enough to cause their oxidation.

b. Benzo(a)pyrine -- Benzo(a)pyrine (BAP) is an undesirable carcinogenic species emitted from combustion engines. Among the factors which affect its concentration in the engine exhaust is the concentration of aromatics in the fuel. Without adding tetraethyllead to the gasoline, the concentration of the aromatic compounds in the fuel has to be increased to arrive at a fuel with a reasonable octane number and combustion characteristics. This might result in an increase in BAP emissions in the gasoline engine exhaust in the future.

A comparison between the BAP emissions in three diesel-cars and for gasoline cars is shown in Figure 11.6 for 1975 FTP cold start, and in Figure 11.7 for 60-mph, steady-state conditions.[103]

BAP emissions in the diesel exhaust are fairly low under combined cold starting and 60-mph, steady running if compared with the gasoline engine. The diesel-engine BAP emissions are of the same order of magnitude as the stratified-charge engines.

The above observations are for a limited number of vehicles; additional data covering a larger number of vehicles are needed to study the BAP emissions from different types of automotive engines.

c. Sulfur compounds -- The concentration of the sulfur compounds in the exhaust is directly related to the sulfur content of the fuel. The *Federal Register* specifies the sulfur content to be 0.05%-0.20% for type 1-D and 0.2%-0.5% for type 2-D diesel fuel and less than 0.1% for gasoline. Figure 11.8 shows the sulfur dioxide and sulfuric acid mass emissions in grams per mile for two gasoline- and one diesel-powered car, and the percent of sulfur converted to H_2SO_4.[93] The tests are at 60 mph, steady-state running conditions. The H_2SO_4 mass emissions are almost the same for the diesel and gasoline engines, in

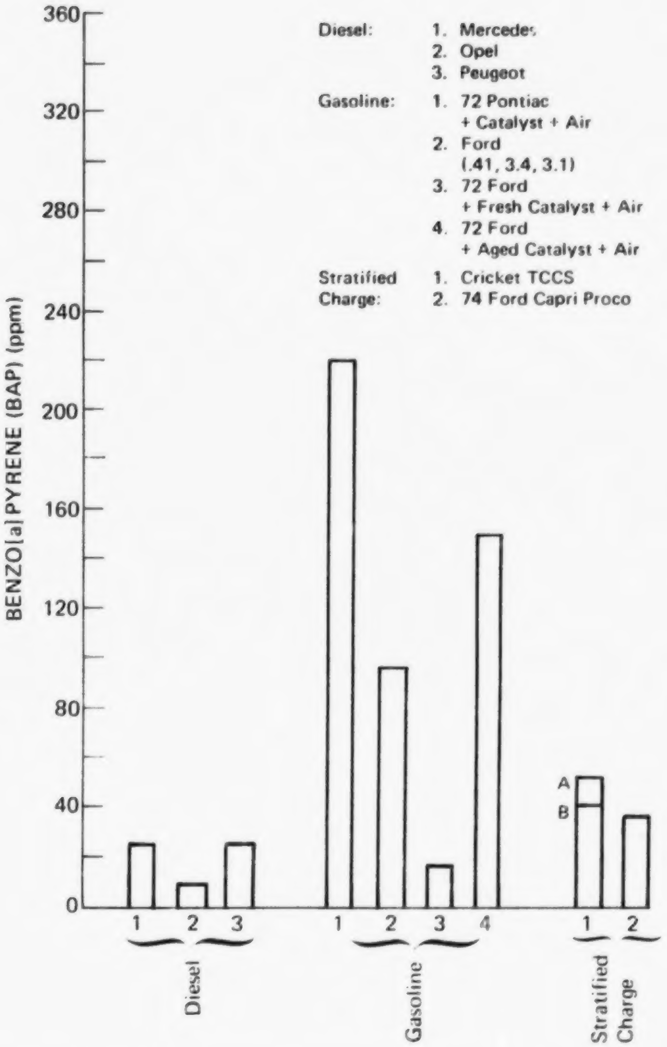


FIGURE 11.6 Benzo(a)Pyrene Emissions from Different Automotive Engines, According to 1975 FTP-Cold Start.

Source: Reference 103

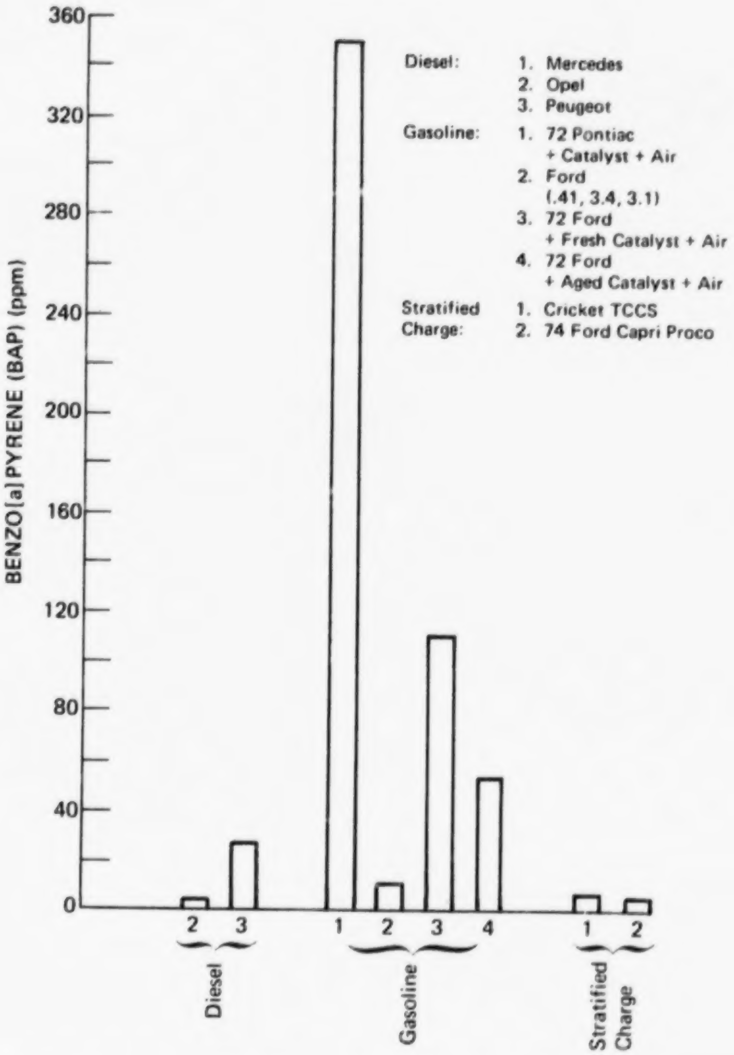


FIGURE 11.7 Benzo(a)Pyrene Emissions from Different Automotive Engines at 60 mph Steady Running Conditions.

Source: Reference 103

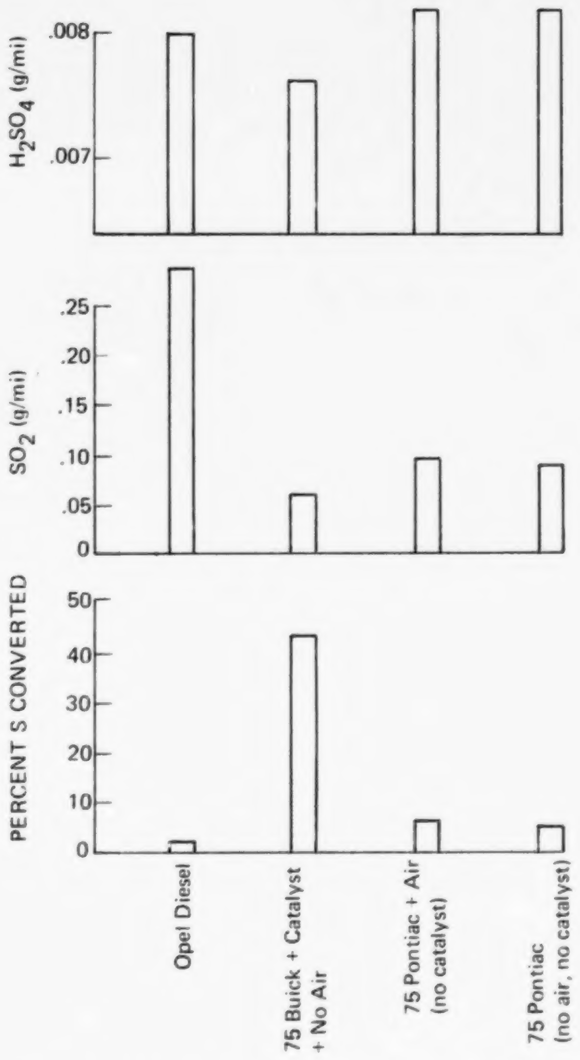


FIGURE 11.8 Sulfur Compounds Emissions from Different Cars.

Source: Reference 93

spite of the fact that the sulfur content of the diesel fuel used in these tests was 10 times that of gasoline. The SO_2 emissions in diesel exhaust are about three or four times that of the gasoline exhaust.

The control of SO_2 and H_2SO_4 emissions in the diesel exhaust can be achieved in the refinery by reducing the sulfur content of the fuel. This may cause an increase in the fuel cost.

d. Aldehydes -- The aldehydes are partially oxidized hydrocarbons and are mainly formaldehyde. Other aldehydes emitted from combustion systems are higher aliphatic aldehydes, aromatic aldehydes, and aliphatic ketones.

All of the results in this Section are reported as formaldehyde HCHO.[104] The aldehyde emissions are given in Table 11.3[103] for two cars equipped with diesel engines, two with models of Wankel engines, four with gasoline engines, two with stratified-charge engines, and one with a gas turbine. The results[103] are for the emissions during 43 minutes of the Modified Federal Cycle Cold Start (MFCCS) and one-hour, steady-state, 60-mph hot start. The results for the Honda and Opel Diesel (reports 1 and 2 in Table 11.3) are for the original Federal Cycle Cold Start. The MFCCS aldehydes are plotted for the Peugeot and other cars in Figure 11.9. It is noticed that the cars powered with engines using a heterogeneous mixture (except for Ford PROCO) produce higher aldehyde emissions. The Ford PROCO car is equipped with a catalytic converter.

The aldehyde emissions under the steady-state, 60-mph test, are shown in Figure 11.10.

The contribution of the aldehydes to air pollution should not be overlooked since their specific reactivity is higher than many unburned hydrocarbons[105] in photochemical smog formation. Also, their effect on health and plant damage is worse than many unburned hydrocarbons.[106]

TABLE 11.3

Aldehydes and Ammonia Emissions from Different Types of Cars

Report No.	Vehicle	HCHO PPM		NH_3 PPM	
		MFCCS	60 mph S.S.	MFCCS	60 mph S.S.
1*	Honda Prototype Civic CVCC engine	1.7	64.5	3.5	9
2*	1973 Opel Diesel	17.5	18.5	19.4	38.9
3	Peugeot, 4 Sp. trans., Diesel Fuel #2	602.5	253.9	11.1	7.28
4	RX2 Mazda D1527 (Thermal Reactor and a reactor by-pass) air pump and EGR	924.6	2,341.6	8.8	32.9
5	EPA Williams Gas Turbine	349.1	80.53 (50 mph)	15.14	28.20
6	Yellow Mazda RX3 (Equipped as in Rep. #4)	381.6	1,541.3	9.32	89.37
7	72 EPA Ford, durability Catalyst, Veh. 24A51	14.67	3.1	3.37	0.88
8	72 EPA Ford, SLAVE Catalyst, Veh. 24A51	74.04	26.29	2.52	0.75
9	Mazda D1527 RX2 Silver (Equipped as in Rep. #4)	862.9	1,385.1	5.81	32.5
10	Pontiac 1972 GM 2477 with 1975 hardware with 30,768 miles	21.41	23.3	20.7	17.35
11	Yellow Mazda RX3 (Equipped as in Rep. #4)	345.56	1,479.8	10.9	36
12	EPA Ford, 1973, A 342-25 (designed for HC = 0.41, CO = 3.4 and NO_x = 3.1)	71.67	149.83	25.31	7.28
13	Mazda RX3 (Equipped as in Rep. #4)	592.9	1,564.1	14.03	36.5
14	1974 Ford Capri EPA 0191 (PROCO)	38.86	31.46	6.53	13.67
15	EPA CRICKET TCCS #8 (with catalytic converter)	524.6	181.9	1.72	1.29
16	EPA CRICKET TCCS #8 (with catalytic converter)	805.2	204.1	1.32	.57
17	Mazda RX3 7,226.0 miles	665.7		5.74	

*Reports 1 and 2 were on the original federal cycle cold start.

REF 103

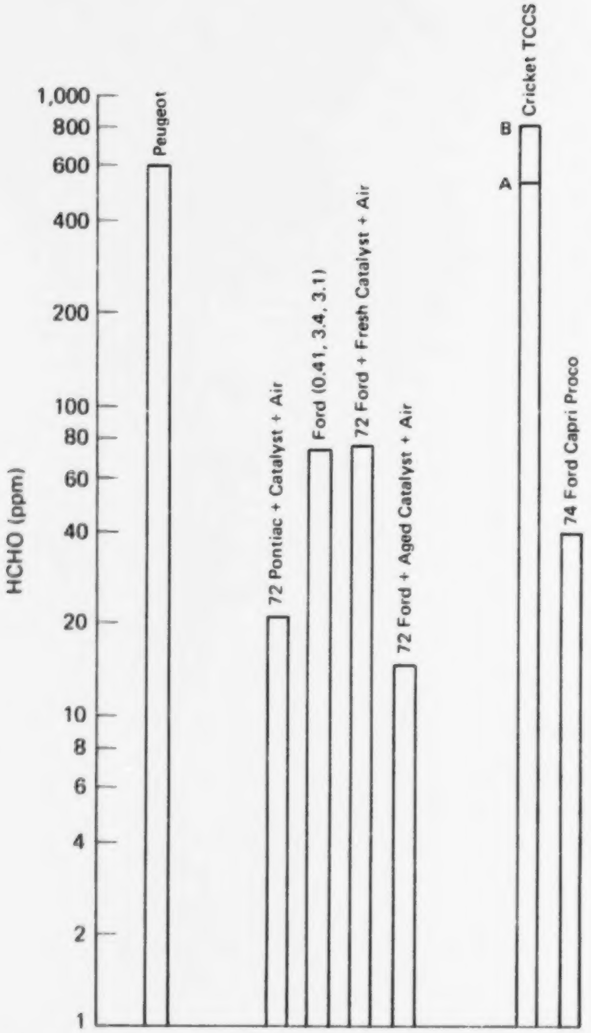


FIGURE 11.9 HCHO Emissions for the Modified Federal Cycle Cold Start (MFCCS).

Source: Reference 103

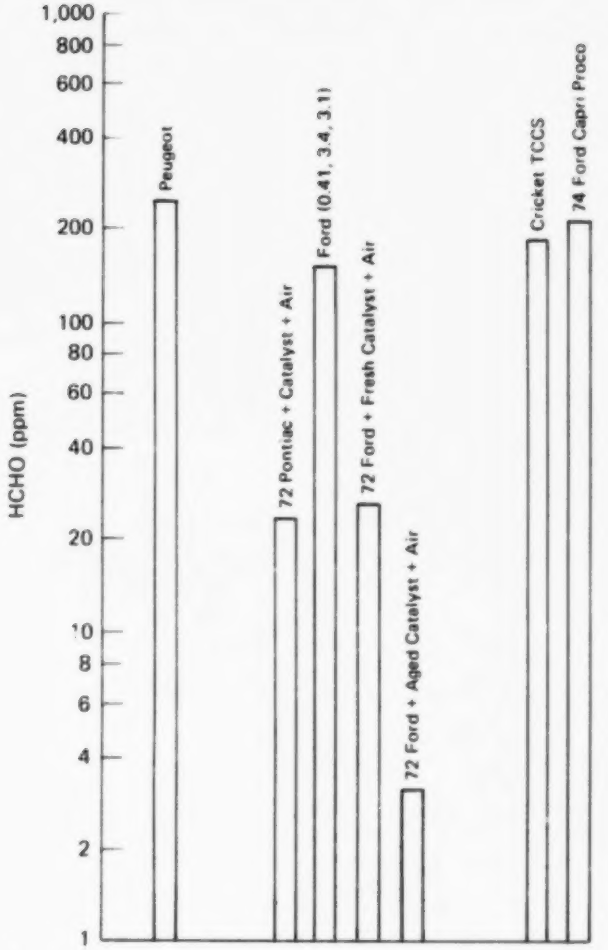


FIGURE 11.10 HCHO for 60 mph Steady Running Conditions.

Source: Reference 103

e. Ammonia emissions -- The NH_3 emissions from the diesel and other engines are shown in Table 11.3.[103] It is noticed that NH_3 is emitted from all the combustion engines. A conclusion for the NH_3 characteristics of each engine is difficult to make at this stage, because of the limited amount of experimental data.

11.4 Fuel Economy

The better fuel economy of the diesel engine over the gasoline engine is the result of its higher compression ratios, higher air/fuel ratios, and the absence of the throttle valve for load control in the diesel. Accordingly, the superior fuel economy of the diesel is at part loads.

The following figures show comparative economy results for diesel- and gasoline-powered cars, in many application. Figure 11.11 shows the results submitted by Daimler-Benz (Ref.98 p. 769) for the miles per gallon of the MB220D diesel and the 1975 MB230 gasoline engine under steady-state conditions and at speeds up to 75 mph. Both cars have an I.W. = 3,500 lbs. The savings in fuel consumption in the diesel car varies from 53% at 30 mph to 32% at 70 mph. Under the CVS test, the MB220 diesel averages 23.6 mpg as compared to 13.9-17.2 mpg for the 1975 gasoline engine; i.e., an average saving of 27% to 41% in fuel consumption. Recent results obtained from EPA Ann Arbor[107] show that the 1975 MB240D diesel car averages 23 mpg, which makes it as economical as the MB220D.

It should be noted that part of the fuel saving in the above comparison is caused by the lower horsepower of the diesel engine as compared to the gasoline engine. A comparison by Opel,[99] based on engines of equal power output fitted in the same car, is given in Table 11.4.

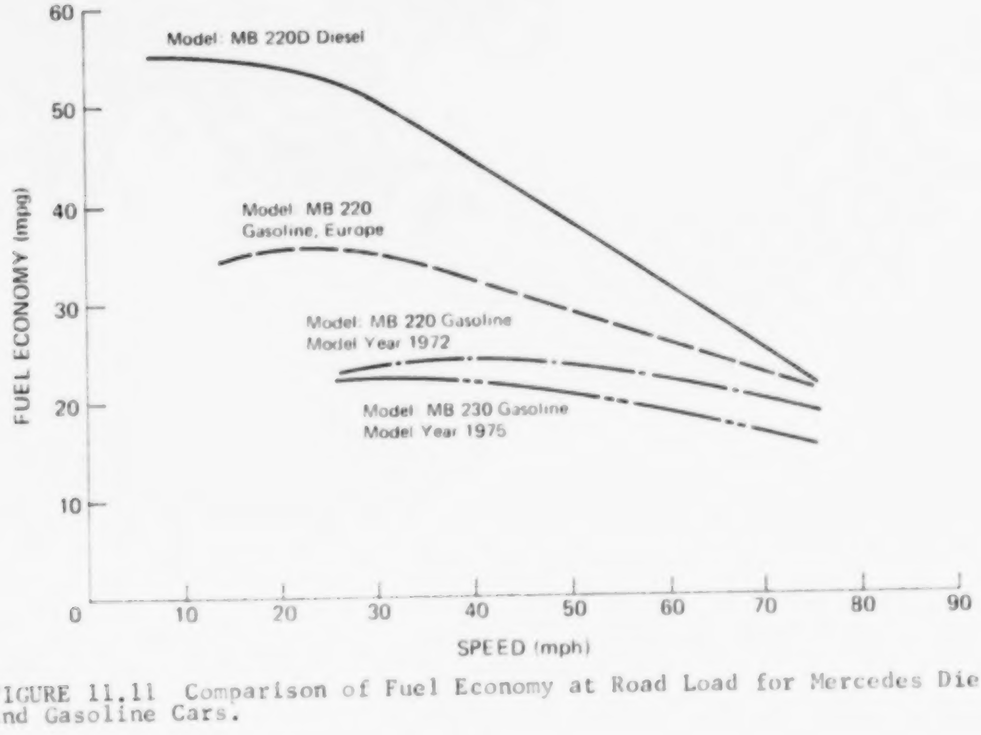


FIGURE 11.11 Comparison of Fuel Economy at Road Load for Mercedes Diesel and Gasoline Cars.

Source: Reference 98

TABLE 11.4

Comparison Between Opel Diesel and Gasoline Cars

	Diesel Car	Gasoline Car
Car Weight, lbs	3,070	2,750
Engine Displacement, CC	2,110	1,618
Miles Per Gallon (mixed-duty cycle)	34	27
Saving	21%	

REF. 99

A similar comparison based on equal power is reported by Peugeot[108] on their 504 diesel and 404 gasoline engines. Here the average saving in fuel consumption is 26%.

A comparison[109] between two foreign diesel cars and an American car, all having the same weight (3,000 lb), is shown in Figure 11.12 for steady-state operation and in Figure 11.13 for city, suburban, and average-driving conditions. Here the average saving in fuel consumption is 36% for the two diesel-powered cars. It should be noted that a part of this saving is caused by the use of manual transmissions in the diesel cars as compared to an automatic transmission in the gasoline car.

The saving in fuel consumption in taxi application in two European cities is shown in Table 11.5.[110]

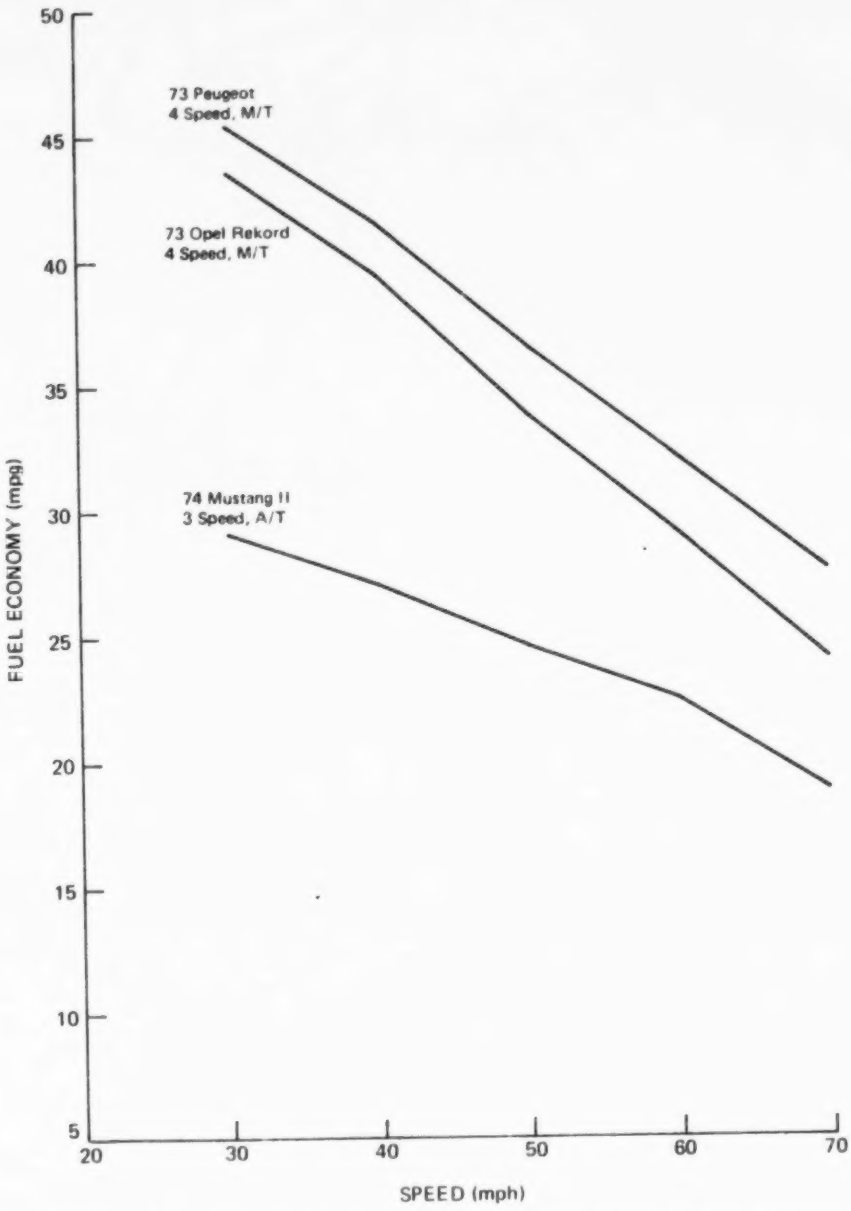


FIGURE 11.12 Comparison of mpg for Different Cars Under Steady State Conditions.

Source: Reference 109

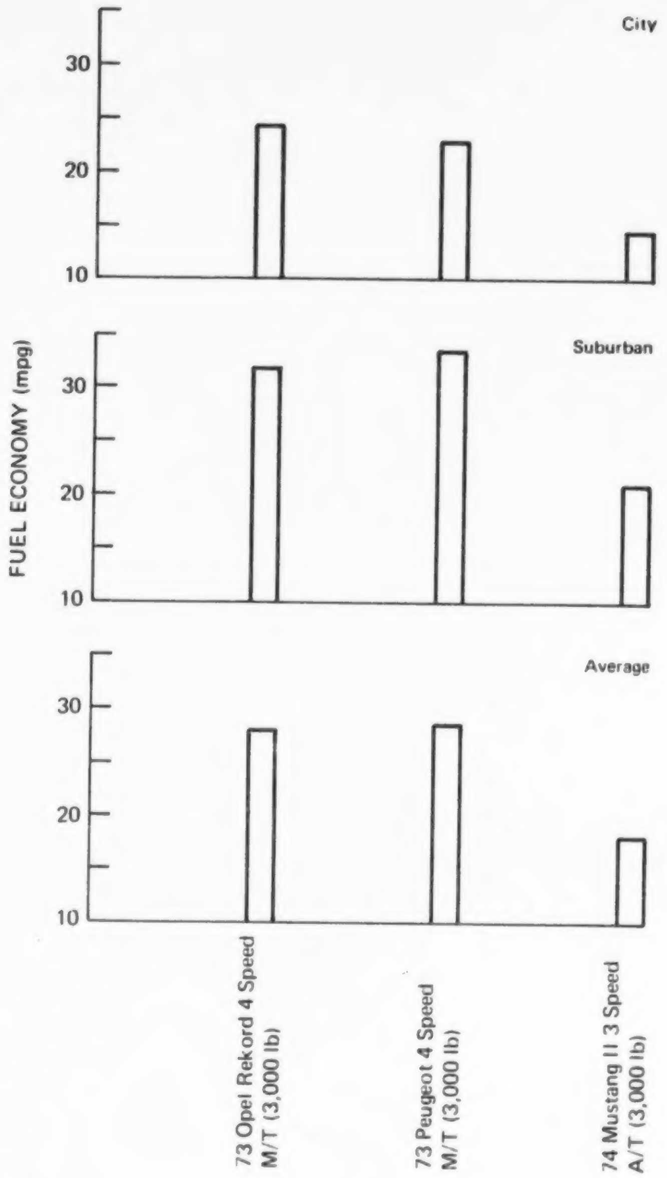


FIGURE 11.13 Comparison of mpg for Different Cars Under City, Suburban and Average Driving Conditions.

Source: Reference 109

TABLE 11.5

Fuel Economy in Taxi Application

	Miles per gallon		
	Diesel	Gasoline	Saving
London Taxi	30.6	15.9	48%
Paris Taxi	31.4	21.7	31%

REF. 110

Similar savings in fuel consumption have been reported by replacing the gasoline engine with a diesel engine in U.S. Post Office one-half, one-and five-ton vehicles[111] and in vans equipped with Perkins diesel engines.[100]

Part of the higher miles per gallon for the diesel-powered car is caused by the higher energy content of one gallon of diesel fuel as compared to the same volume of gasoline, as shown in Table 11.6 (Ref.98 , p. 850).

TABLE 11.6

Comparison Between Diesel and Gasoline Fuels

Fuel	Average mass per gallon	Average BTU per gallon
Diesel	7.1	137,750
Gasoline	6.0	123,500

REF. 98

The increase in the energy content of one gallon of diesel fuel is 12% above that of gasoline.

From a total energy point of view, the energy expenditure in producing the fuel at the refinery should be taken into consideration. Diesel engines can use a wide range of distillates which are produced at a lower cost than gasoline.

In summary, the average saving in fuel consumption by using the diesel engine instead of the gasoline engine in passenger cars varies between 25% to 50%.

11.5 Initial and Maintenance Costs

Diesel engines initially cost about 50% more than gasoline engines. Half of this difference is attributed to the high cost of the fuel-injection system,[102] and is partially caused by its limited mass production.[112] For a diesel engine to have the same power as a gasoline engine, it should have a larger displacement volume, since the air utilization is less. Also, it should have heavier parts to stand the much higher gas pressures produced in the cylinder as a result of the higher compression ratio used. These, too, increase production costs of the engine. The heavier starting motors and batteries required to overcome the high compression pressures and to the production cost of the diesel-powered cars.

However, the maintenance cost for the diesel engine is lower than that for the gasoline engine. The injection system does not require the frequent maintenance and replacement of parts experienced with the ignition system and carburetor of the gasoline engine, although there is a slightly higher cost for each service. On the other hand, routine maintenance (oil and filter change) is more frequent for the diesel engine.

Daimler-Benz reported the initial and maintenance costs for their MB 1975 gasoline and diesel cars.[113] These costs are given in Table 11.7. The maintenance cost includes general maintenance (spark

TABLE 11.7

Initial and Maintenance Costs and Performance of Mercedes 1975 Cars *

	Diesel 240D	Gasoline 2.3L	
		California Model	Federal Model
Vehicle Weight, lb	3,500	3,200	3,200
Horsepower	65	95	95
Weight-Power Ratio lb/HP	6.8	2.6	2.6
Fuel Economy mpg	21-22	16.2	15.5
Acceleration time, sec 60 mpg	24.6	13.7	13.7
Initial Cost			
Maintenance Cost for 100,000 miles	$1,153	$2,590	$2,590
Initial Price (1974 Model)	$8,715	$8 420	$8,420
Total Cost for 100,000 miles (assuming 1974 Model Prices)	$9,868	$11,010	$11,010

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*The initial cost for the Mercedes 1975 cars had not been announced by the company at the time of writing this report. The initial prices for the 1974 models are used for comparison.

REF 113

plugs, tuning, oil changes, etc.) and two catalyst changes for the gasoline car. The larger cost differential between the two cars in 1975 is the high cost for the catalyst change which was quoted at $600 for this six-cylinder and $800 for the eight-cylinder gasoline engine. The 1974 maintenance costs are $1,132 for the diesel and $1,062 for the gasoline engine.

At 23 mpg for the 1975 diesel car and 16 mpg for the 1975 gasoline car, and at 45¢/gal for the diesel fuel and 55¢/gal for gasoline, the fuel cost for 100,000 miles would be $1,957 and $3,438 for the diesel and gasoline cars, respectively. For the sake of comparison, considering 1974 model prices, the estimated total initial maintenance and fuel costs are $11,825 for the diesel and $14,448 for the gasoline car. This means a saving of 18% to the owner of the diesel-powered car.

The superior economy of the diesel-powered car over the gasoline-powered car is manifested in applications involving part-load operations. For example, taxicab fleet owners in London and other cities in Europe had to shift from the gasoline to the diesel engines to make a profit while keeping the fares within the limits imposed by the local authorities.

Diesel engines proved to be economical in taxicab fleet operations even in countries where the price of the diesel fuel is equal to or slightly higher than gasoline fuel, such as in Great Britain. In other countries where diesel fuel is less expensive than gasoline, the savings increase proportionally.

The present higher initial cost of the diesel-powered car over the gasoline car is expected to diminish in the 1975 model cars and those that follow. For 1975 California cars and 1977 nationwide cars, the gasoline-powered cars should be equipped with catalytic converters and feedback systems. Some of the gasoline engines will be equipped with fuel-injection equipment. All these add-on devices will increase the initial and maintenance costs of the gasoline-powered cars and make the diesel-powered car more economical.

11.6 Driveability -- The driveability of two Mercedes diesel automatic transmission (A/T) vehicles (1969 and 1974 models), a 1973 manual transmission (M/T) Opel Rekord and a 1973 M/T Peugeot were compared to the driveability of a 1973 Pinto and a Honda A/T CVCC vehicle.[109] The results are shown in Figure 11.14. The A/T diesels were better than the one A/T gasoline engine in the following three types of evaluation: minimum driving ratings, drive ratings average, and the idel quality rating. The M/T diesels were better than the Honda CVCC M/T in two categories. However, the Honda CVCC M/T was better in idle quality. Daimler-Benz reported that the driveability of their diesel-powered vehicle is the same as their gasoline-powered vehicle.

11.7 Intrinsic Problem Areas

a. Starting -- Automotive diesel engines which can meet the emissions standards have a prechamber (Mercedes) or swirl-type (Peugeot and Opel) combustion chamber. These types of combustion chambers need a starting aid in the form of a glow plug. Because the glow plug should reach a high temperature before cranking the engine, some delay in starting is experienced. At present, research is being done on a high-intensity glow plug to reduce starting delay.

b. Noise -- The diesel engine is inherently noisier than the gasoline engine, particularly after cold start and during idling. This will be discussed under the noise emission classifications of exterior and interior noise.

Figure 11.15 shows a comparison made by the Ford Motor Company between the exterior noise levels of three diesel-powered cars

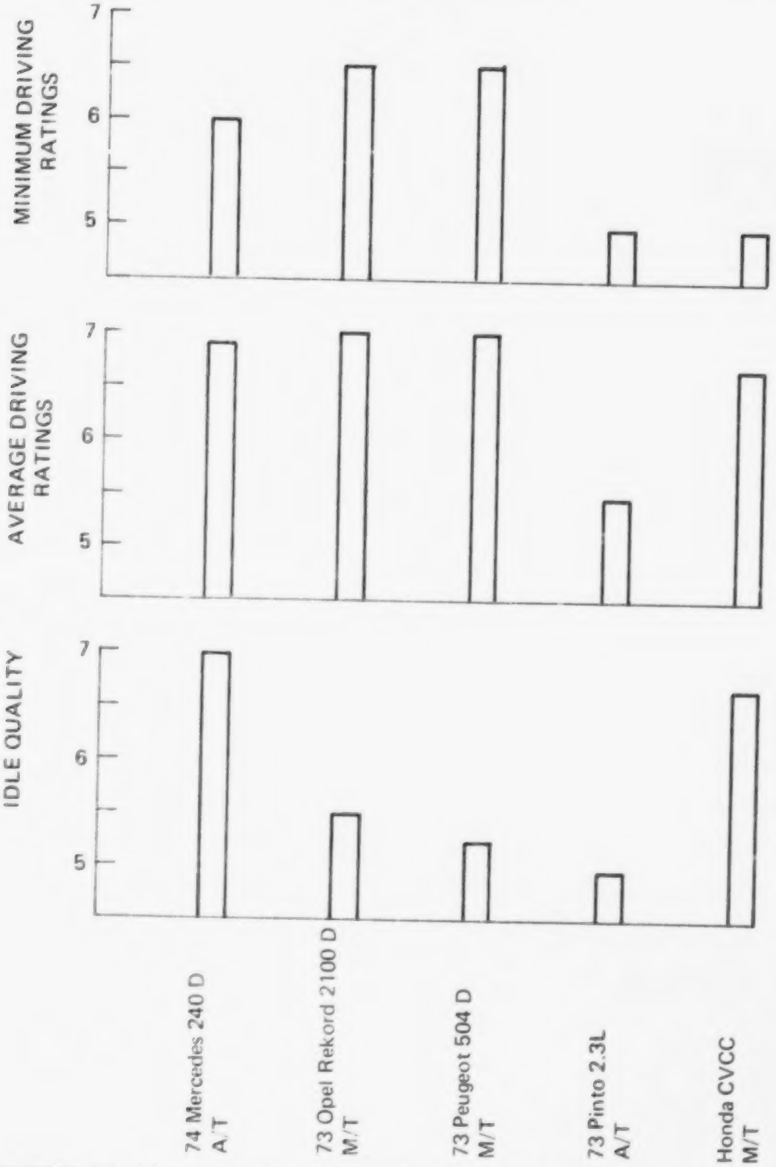

FIGURE 11.14 Comparative Drivability of Diesel Powered and Other Cars.

Source: Reference 109

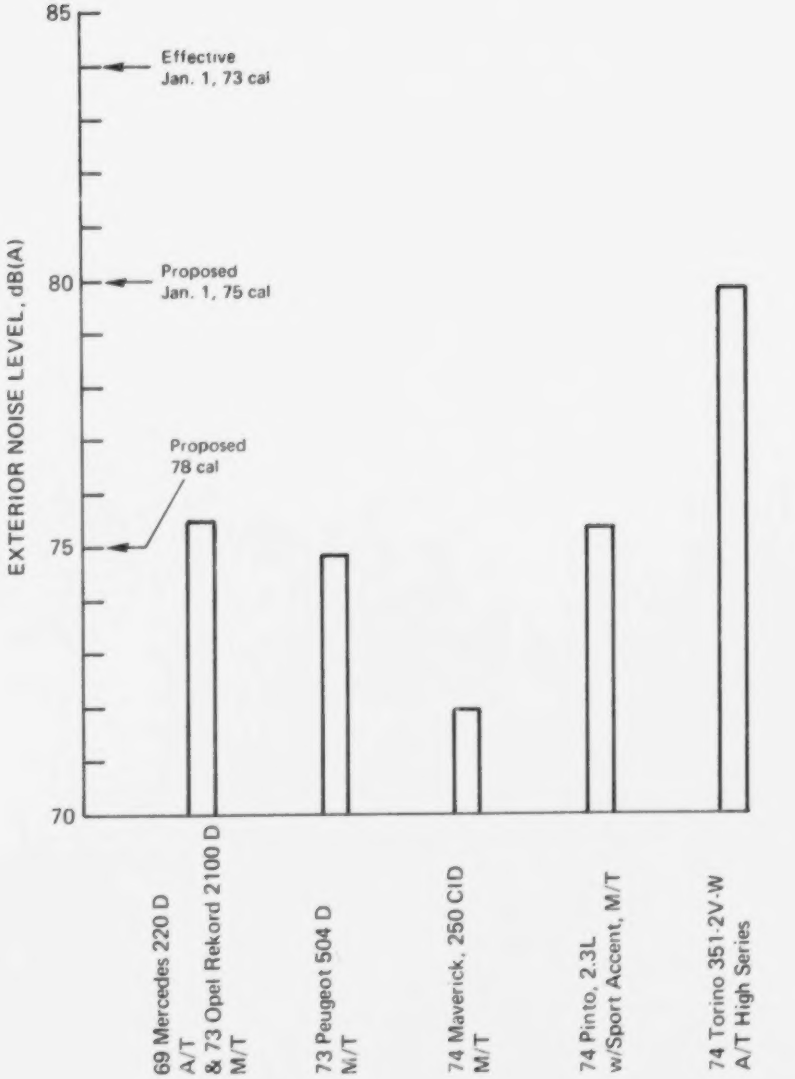

FIGURE 11.15 Exterior Noise Levels from Different Cars.

Source: Reference 109

and three American gasoline-powered cars.[109] This comparison is according to the SAE Standard J 986a test procedures.* This test calls for a wide-open throttle acceleration from 30 mph to maximum engine revolutions-per-minute over a distance of 100 ft, with a microphone stationed 40-50 ft away. The results show that the three diesel engines have lower sound levels than the 1974 Torino and have the same sound level as the 1974 Pinto. Also, these engines meet the present California standards, and those proposed for 1975. The 1973 Peugeot meets the proposed 1978 California standards. The 1969 Mercedes and the 1973 Opel are 0.5 dB above the proposed 1978 California standards.

Recent comparative noise results reported by Southwest Research Institute[94] are shown in Figure 11.16 and Table 11.8 for cars of different makes. Figure 11.16 indicates that some diesel-powered cars produced less exterior noise than the gasoline-powered car and others produced more noise. Also, the diesel-powered cars, except the Mercedes, meet the proposed 1978 California noise standards of 75 dbA. The Mercedes car exceeds the proposed 1978 California standards by 2 dbA, and the Capri PROCO exceeds these standards by dbA.

A comparison between diesel-and gasoline-powered cars of the same make are shown in Figure 11.17. The noise levels of the Mercedes 220D diesel and 220 gasoline cars are shown in Figure 11.17 for different driving modes (Ref. 98, p. 773). The diesel produces noise levels of 1 dbA to 5 dbA higher than the gasoline engines. The diesel car is particularly noisy during engine start up and idling. The noise levels of the Peugeot 504 diesel car are higher than the

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*SAE -- Society of Automotive Engineers

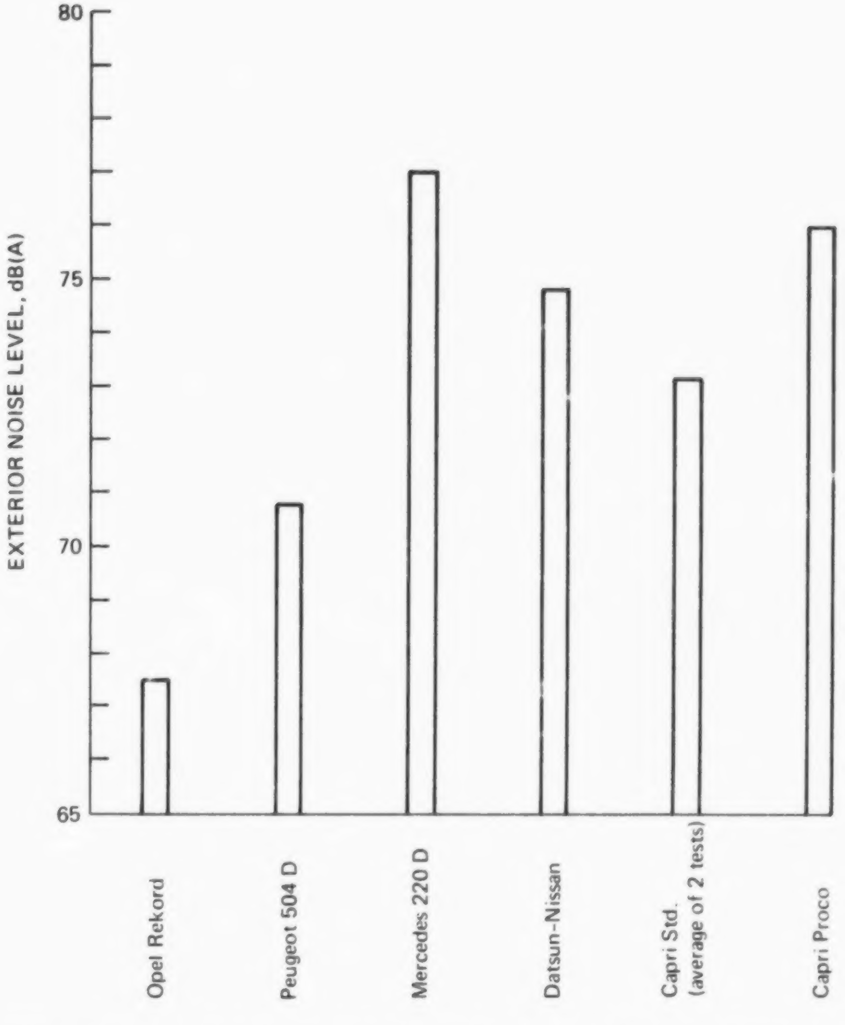


FIGURE 11.16 Exterior Noise Levels from Different Cars.

Source: Reference 94

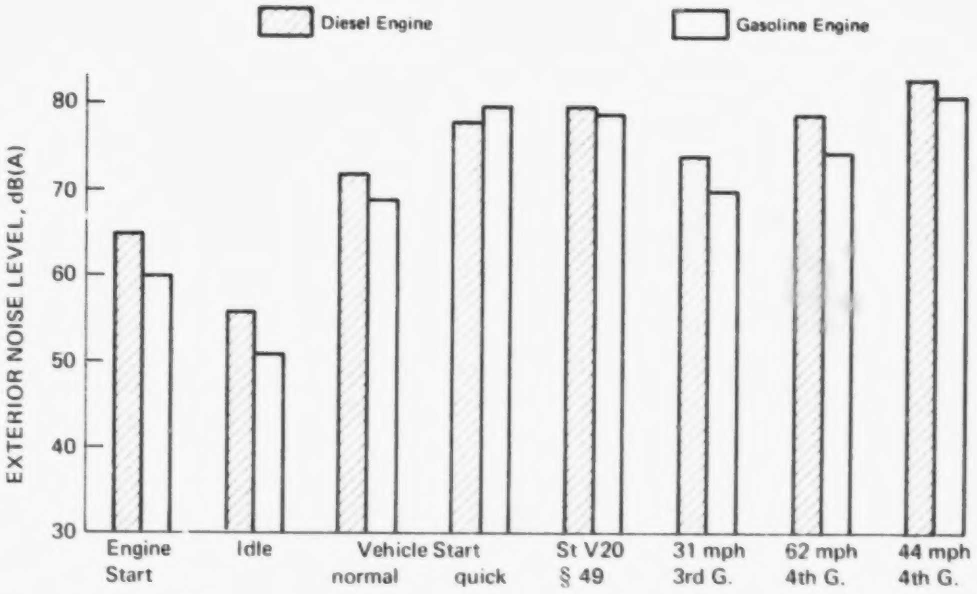


FIGURE 11.17 Comparison of Exterior Noise Levels for 2.2 Liter Mercedes Gasoline and Diesel Cars.

Source: Reference 98

TABLE 11.8

Comparison Between Exterior and Interior Noise Levels of Diesel-and-Gasoline-Powered Cars

	Datsun Nissan	Mercedes 220D	Capri Std	Peugeot 504D	Opel Rekord	Capri PROCO	Capri Std
Date Tested	3-6-74	3-5-74	3-6-74	3-26-74	3-26-74	3-26-74	3-26-74
SAE J986a Accel Driveby							
Exterior	74.8	77	73	70.8	67.5	76	73.3
Interior							
Blower On (1)	84	78.8	82.3	80	73.8	83	83
Off	83.3	74.3	81.5	78.5	73.5	83	82.5
48.3 km/hr Driveby							
Exterior	63.3	62 (2)	58.1 (2)	61.3	62.5	58.5	58
Interior							
Blower On (1)	71.3	73.5	70.5	72.3	70	72.3	71.8
Off	69.5	63.5	65.8	66.5	69	70.5	66.5
Engine Idle							
Exterior (3)	79	66	63	68	72	63.5	57.5
Interior							
Blower On (1)	67	71.5	70	70	70	71	70.5
Off	66.8	51.5	54	52.3	53.3	66	53

(1) Windows Up, Fresh Air Blower on High

(2) at 7.62 m

(3) at 2.54 m

REF 94

Peugeot 504 gasoline car by 4 dbA during idling and 2 dbA at 31 mph. The two cars have equal noise levels at 50 mph and 62 mph. At 74 mph, the diesel car is noisier by 2 dbA, (Ref. 98, p. 839).

Table 11.8 also shows the results of many tests conducted by Southwest Research Institute according to the Federal Clean Car Incentive Program.[94] These results also show that the exterior drive by and idle noise for the diesel cars is higher than the gasoline powered cars.

A comparison[109] between the steady-state interior noise levels (A-weighted-dbA) of three diesel vehicles and those of a 1974 Torino and a 1974 Pinto 2.3L are shown in Figure 11.18 for speeds ranging from 20 mph to 60 mph on a smooth asphalt road. The results show that the Torino is fairly quiet compared to the diesels, but that the Pinto has nearly the same noise levels.

It should be noted that the interior noise depends to a great extent on the packaging of the engines, the structure of the car, interior design and blower noise.

Table 11.8 shows that some diesel cars have lower interior noise levels than gasoline cars and that this noise level depends on whether the blower is on or off.

The noise level of diesel engines may be reduced by modifications to the fuel injection system, changes in injection timing, use of pilot injection, structural changes, basic changes in engine design (such as using more cylinder of smaller bore, etc.), intake and exhaust-manifold modifications, and engine isolation techniques.

c. Odor -- The odor produced by the diesel engine is caused by products of the auto-ignition process. Even gasoline engines produce odor if they run on or "diesel".

Little research work has been done to define which of the stages of the auto-ignition process produce the characteristic odor.

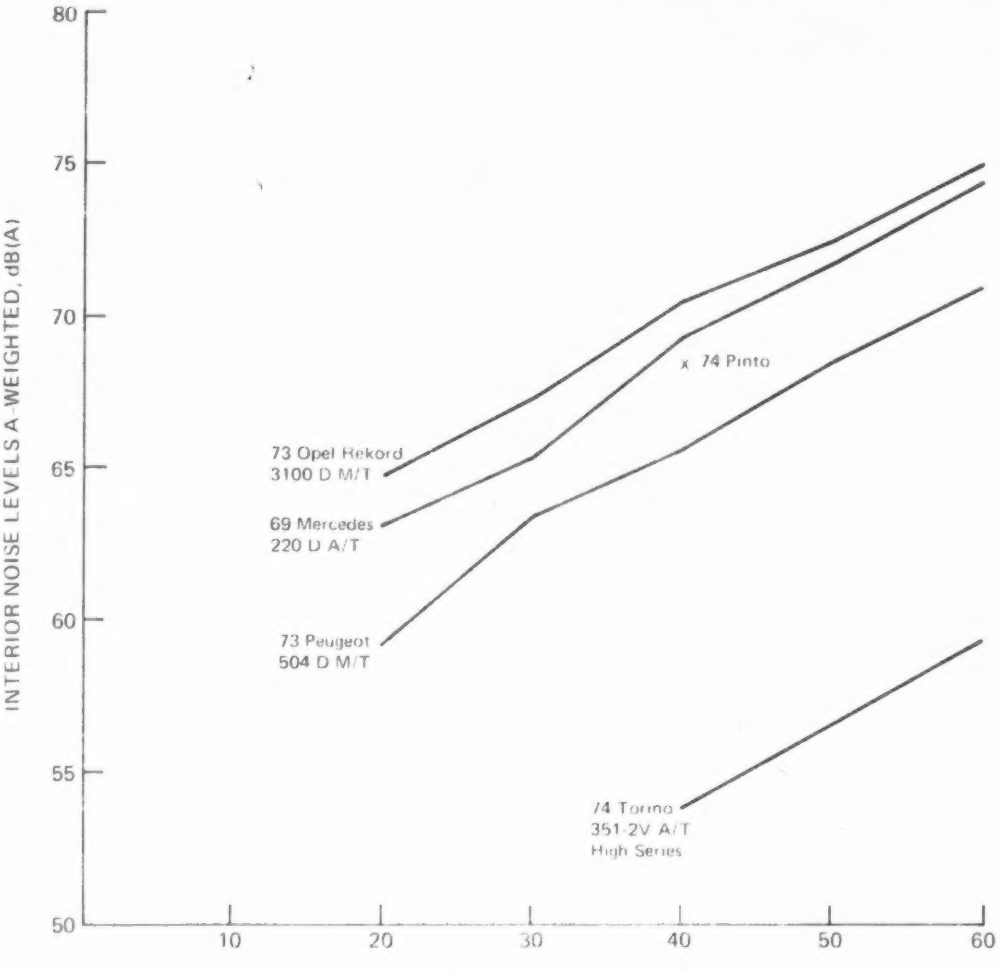


FIGURE 11.18 Interior Noise Levels from Different Cars.

Source: Reference 109

One research program, using n-heptane-air mixtures, in a motored CFR engine, indicated that odor is the result of quenching the second stage (cool flame) in the auto-ignition process.[97] Table 11.9[94] shows the results of a comparison of the exhaust odor from four diesel-powered cars, two gasoline cars and a PROCO Capri car. These exhaust-odor results are for 10 driving modes covering the whole range of loads and speeds. The averages of all 10 modes show that the odor from the diesel cars is, in general, higher than that from the gasoline or PROCO cars.

The use of exhaust-catalytic converters to reduce odor, and other incomplete combustion products in the diesel exhaust,[114] is still in the research stage. It is not expected that it will be applied to the actual engine in the near future.

Further basic research is needed to study odor control.

d. Low power-weight ratio -- The diesel engine produces less power than the gasoline engine of equal displacement, for two reasons. First, the overall fuel/air ratio in the diesel is always leaner than the stoichiometric ratio. The limit to the increase in fuel/air ratio is smoke production. Second, the maximum rated speeds in diesel engines are less than in gasoline engines. The limit here is the short time allowed for fuel injection, evaporation, mixing and combustion for proper engine operation. Mechanical-stress considerations also limit the speed of the diesel engine.

The low power/weight ratio causes the diesel-powered car to take a longer time for acceleration. Table 11.7 shows that time for acceleration from 0 to 60 mph is 13.7 seconds for the Mercedes 2.3L gasoline engine, and 24.6 seconds for the 240D diesel car. For the Peugeot 504 diesel this time is 23.6 seconds, and it is 16.2 seconds for the 504 Peugeot gasoline engine.

TABLE 11.9

Comparison of Odor from Diesel-and Gasoline-Powered Cars

Type Fuel	Car	Six Steady States	Idle	Three Trans.	All Ten Conditions
Diesel	Datsun-Nissan W	3.4	2.9	4.7	3.8
	S	3.2	2.7	4.6	3.6
	Mercedes 220D	3.0	3.1	3.7	3.2
	Peugeot 504D	5.2	4.8	5.7	5.3
	Opel Rekord	3.9	3.3	4.1	3.9
Gasoline	Ford LTD	1.5	1.2	1.5	0.6
	Standard Capri	3.0	3.3	2.9	3.0
	PROCO Capri	1.0	0.7	1.6	1.1

REF 94

Turbocharging is an effective tool for improving the power/weight ratio of the diesel engine. Turbocharging increases the maximum power, torque and rated speed of the engine. This improves the acceleration characteristics of the vehicle. The effect of turbocharging on fuel economy and emissions from the diesel-powered car is presently being studied by many manufacturers. The present attempts are being made by adding a turbocharger to existing diesel engines without lowering their compression ratio or optimizing the injection and combustion processes. The results of these attempts are not conclusive. The penalty in fuel economy at idling and low loads as a result of turbocharging depends on the design of the intake and exhaust systems and the degree of matching the turbocharger to the engine. The effect of turbocharging on the emissions during a FTP cycle has not been assessed.

11.8 Conclusions

a. Technological feasibility of meeting the different emission standards:

(1) Diesel engines, currently mass-produced to power passenger cars of 3,000 lb to 3,500 lb, can meet the 1977 standards without EGR, add-on exhaust treatment or feedback systems.

(2) There is no penalty in the initial cost, maintenance cost, or fuel economy of these engines in meeting these standards.

(3) These diesel engines proved to be the most economical power plants as far as fuel consumption is concerned and are as reliable and durable in the field as the non-controlled gasoline engine.

(4) The total cost to the owner for one of these mass-produced 1975 cars, including initial, maintenance and fuel cost for 100,000 miles, will be less than that for the equivalent gasoline-engine car.

(5) No extraordinary maintenance is required in the field during the useful life of the vehicle due to the absence of catalytic converters and feedback systems and the high durability of the diesel engine.

b. 1978 Nationwide standards

(1) Based on the presently known technology, it is not feasible for the diesel-powered car to meet the 1978 NO_x standards of 0.4 g/mi.

(2) If the NO_x standard is relaxed to 1.5-2 g/mi, many currently mass-produced, diesel-powered cars would be able to meet the standard without any penalty in initial, maintenance or fuel cost. Thus, the diesel-powered car would be superior to the gasoline version in total cost to the customer, and in reliability and durability.

(3) With the application of EGR, injection-system modification and injection retard, it may be possible for currently produced diesel-powered cars to meet NO_x levels of 1.0 g/mi., but this may result in a penalty of 5% to 15% in fuel economy and power. The effect on durability of the engine has not been assessed.

(4) Levels of NO_x, slightly less than 1.0 g/mi (but not less than 0.6 g/mi) might be reached by diesel-powered cars if sufficient research is conducted to optimize all the NO_x-control techniques.

c. Problem areas

(1) Intrinsic problem areas in the diesel powered cars which deserve further research are: particulates, odor, noise, and low power/weight ratio.

(2) The future standards for the nonregulated emissions should of course, take into consideration the harmful effect of the pollutants rather than the total mass of the emissions. For example, one gram of aldehydes may be more harmful to the health and environment than one gram of paraffinic hydrocarbons. Also, the total mass of the particulate emissions may be high in the exhaust of one type of engine, but the mass of harmful species (such as BAP) may be low.

(3) The relaxation of 1978 NO_x emissions should be decided on as soon as possible. The lead time needed for manufacturing is on the order of five years.

12. ALTERNATIVE POWER PLANTS FOR AUTOMOBILES

12.1 Introduction

Activities in alternative power-plant development for automobiles have continued in the two years since Reference 116 was written. Many of the problem areas have been more firmly stated and some of the less applicable power plants have been weeded out. The engine characteristics and development times have become more firm. It is clear that there are no high-performance alternative power plants that can go into mass production before the 1980's.

Alternative heat engines in their major forms are gas turbines, Stirling engines, and Rankine engines. These can be categorized as continuous-combustion engines in which a fire is established and heat is continuously supplied to the system until power is no longer needed. There are a number of other engines that fit into the spectrum represented by these three major types, such as several forms of reciprocating Brayton-cycle engines and super-critical-fluid Rankine cycles. In this Section, concentration will be with the major types. These heat engines can use energy stored in the form of liquid or gaseous fuel. Also, the Stirling and Rankine engines can use energy stored in any fuel and in the form of heat.

Storage batteries have been used extensively for over a century, and these can be used in modified form for powering automobiles without the aid of heat engines. Also, flywheels have been used for over a century, but more recently they have been used to supply power to the drive wheels of busses. With the use of new materials and recent technology, high-performance flywheels can now be designed to be used directly, or as a mechanical energy-storage system for powering an electrical drive for automobiles.

Hybrid systems are combinations of two or more different kinds of power plants or of different versions of similar power plants. The aim of hybrids is to allow the complete system to perform according to the best features of each part. Those hybrids that have been given the most attention in the last few years are battery-heat engine combinations. Some consideration has also been given to combining two different kinds of batteries in an electrical drive system.

Alternative engines for automobiles are in an embryo state of development. While gas turbines, Stirling engines, steam engines, advanced lead-acid battery power plants, and electric-heat engine hybrids have been running in automobiles, there are none that can be considered as suitable prototypes for manufacture. That is, the developers themselves have indicated that at least another generation of development is required before they will be satisfied that their particular power plant has demonstrated its full technical, economic and customer-satisfaction potential. There are no flywheel or flywheel-hybrid power plants presently operating in automobiles; and there are no high-performance, battery-powered systems running in automobiles.

A few examples of experimental continuous-combustion engines have progressed beyond the dynomometer testing stage and are presently mounted in automobiles that are either available, or very nearly will be available, for test driving. These include two Stirling engines (United Stirling and Philips), three gas turbines (Williams Research and Volkswagen, Chrysler, and General Motors), and eight Rankine engines (Carter, Scientific Energy Systems, Steam Power Systems, Pritchard, Thermo-Electron, Aerojet, Kinetics Corp., and Williams Brothers). Other cars, such as GM's steam cars and Rover's gas-turbine car, have operated in the past but their development is now dormant. Others, such as the Paxve Rankine engine car, are in a temporary state of dormancy. All of the active engine programs whose goal is mass application to automobiles are aimed at demonstration and upgrading. Measured performance and engine characteristics that are considered as the final state of development do not exist. Therefore, while some data and quantitative characteristics are reported herein, they are not to be considered as representative of fully developed engines. Most of the information is, per force, tempered by judgment of the source and of the panel of consultants; the conclusions stated throughout this Section are judgments of the latter.

Similar judgment has been rendered in some cases concerning batteries and electric drives. This is particularly true for the high-performance batteries still under development. Also, the electric drive situation is in a state of flux with final choice of system not made in most cases.

12.2 Gas Turbine

In comparison with aircraft and industrial gas turbines, the automotive gas turbine has a much more difficult job and has necessitated considerable development effort. Efficiency, low idle fuel consumption, good off-design performance, and fast response requirements have forced the developers to turn their attention to higher turbine inlet temperatures, simple yet efficient rotating components and highly effective regenerators. Thrust is not needed as in jet engines. Steady load as in industrial gas turbines is the antithesis of automotive gas turbine use. These aspects make the automotive gas turbine unique.

General Motors demonstrated attainment of 1978 emissions standards in 1974.[122] It used an existing engine (GT 225) in an automobile weighing 5,000 lb, running through the federal driving cycle on chassis rolls. A large variable-geometry combustion was fitted and was manually controlled from an off-vehicle console. All four tests made were reported as being below the 1977 limits:

HC	CO	NO_x
	grams per mile	
0.02	2.7	0.32

from cold starts using diesel fuels. Other developments also show low emissions.[123-128] Above 2.0 g/mi NO_x a fixed combustion geometry can be used. Achievement of NO_x as low as 0.4 g/mi requires variable geometry, although the Zwick combustion[125,126] uses only a very simple flow-splitter concept. This combustion was tested on a small gas turbine and yielded the following emissions (translated from g/kg):

HC	CO	NO_x
	grams per mile	
0.26	2.7	0.12

There was general agreement among all companies visited that there was no problem in meeting the hydrocarbon and carbon-monoxide limits with existing gas turbines, and that a level near 2.0 g/mi NO_x could be reached with fixed-geometry combustors. The use of variable-geometry combustors to reach the lower NO_x limits would entail additional manufacturing costs of at least $40 (Ford projection) because of the more complex burner and control system required.

Ford, Chrysler, and GM were in agreement that gas-turbine engines, which would be available for production in the 1980's, would have fuel consumptions in the federal driving cycle lower than the average spark-ignition engines controlled to meet 1974 emissions. Ford, in particular, forecast sharply lower consumption.[129] It felt that the miles per gallon of production vehicles would be 40% higher than that of 1974 spark-ignition-engine cars in 1985 and 130% higher in 1990 (3,000°F TIT). Poor idle fuel consumption has been the chief cause of poor mileage in urban driving, and the higher TIT levels projected tend to reduce this deficiency. Calculations verify that with Ford's projected component performance (turbine efficiency = 91%, regenerator effectiveness = 92%, compressor efficiency = 85%, leakage = 2½%, and pressure drop = 10%), and with a turbine inlet temperature (TIT) of 2,500°F, that the projected fuel economy is reasonable to obtain. The component efficiencies listed above are on the optimistic side, which implies that very careful development will be required to achieve the above-mentioned fuel economy. Ceramic turbines, nozzle rings, combustors, and heat recovery units are required to achieve the full advantage in fuel economy.

The most significant change in the outlook for the gas turbine results from the general agreement among U.S. manufacturers[122,129-131] that it can be a technically superior engine to the spark-ignition engine at least down to 100 hp, and probably to 75 hp. If Ford's predictions are confirmed, a 75-hp gas-turbine engine would have a lower fuel consumption than a 40-hp spark-ignition engine, thus tending to rule out the use of minicars as a necessity to reach high mileage.

Moreover, gas turbines of any size are intrinsically long-life engines, as demonstrated in the aviation industry. Their use will give an incentive to the design of long-life chassis and to the consequent reduction in materials use. In contrast, spark-ignition, internal-combustion engines as used in automobiles are comparatively short-life engines, with life decreasing as size decreases.

The configuration of the gas turbine for automotive use, which has been regarded as standard, has a centrifugal compressor, one or two rotary regenerators, a combustor, and an axial turbine as the so-called 'gasifier' section, and a separate-shaft axial turbine with variable-angle nozzles forming the power section.[130-136] This basic configuration was used by GM in their demonstration of low emissions.

In the last two years, there has been increased study of[137] and acceptance of the single-shaft gas turbine concept[122,129] which achieves considerable simplification by dispensing with the power turbine. However, some form of infinitely variable transmission is required to take power from the shaft driving the compressor, whose speed must be maintained at above 50% design speed. Various types of transmission are being studied, but none has yet been demonstrated with a single-shaft gas turbine.

Present U.S. vehicle turbines use peak-cycle temperatures in the range of 1,850°-1,925°F.[122,129-131] It is generally accepted[129,131] that 2,200°F is achievable with existing technology. It is anticipated that temperatures will be increased over the next six years to 2,500°F,[129,130] and possibly to 3,000°F.[122] The most likely means for withstanding these temperatures in the combustor, nozzle and turbine is the use of silicon carbide or silcon nitride. Ford, with in-house and ARPA funding, is developing a dual-density turbine wheel with a hot-pressed hub and molded blades, both of SiN_2. Indicative of the increasing effort on ceramics for gas turbines are References 138-142, showing the high potential of silicon carbide and silicon nitride. Alternative ways of reaching high temperatures are to use gas or liquid cooling and to employ coated refractory (molybdenum) alloys.

Design of gas turbine for the high inlet temperatures required to achieve competitiveness with gasoline engines is a new science that is some years away from maturity. Casting and firing ceramics, use of refractory metals, and strong cooling of blades and nozzles are all expensive at this time. They are all in the early development stages for automobile engines. There is no established certainty that any of these methods of utilizing high turbine inlet temperatures can be developed for a low-cost engine. Also, there is some feeling among development engineers that the potential performance gains associated with higher turbine inlet temperatures will be dissipated by increased losses due to the reduced Reynolds number.[143]

The cost of anti-friction bearings can be high. Chrysler uses plain bearings presently.[130] Gas bearings of the foil type seem attractive as a future development.[129]

Present problems with ceramic heat exchangers have been identified as due principally to sodium substitution from road and sea salt.[129] New ceramic materials will be required. Some potential candidates have been found and are being evaluated.

Studies have been made, and are continuing, on gas-turbine costs to the consumer.[130,131,144] Above 150 hp, it is possible that they could be near competitive with spark-ignition engines,[131] but they become much less competitive below 100 hp.[143] The cost structure is not clear at this time and must be made firm with more experience in small gas-turbine manufacturing.

The estimates made in the April 1973 report (Reference 116) still seem valid--that limited production of gas turbines could start in 1982 and mass production in 1984. These estimates assume an intense and continuing effort.

The costs of changing the automobile industry's 46 engine lines to gas-turbine production (ceramic components) have been estimated by Ford to be $250 million each, or a total of $11.5 billion.[129] This cost would be additional to the normal costs of production changes. Ford's estimates show the possibility of the investment being equalled by the value of the fuel saved (at about 65 cents per gallon) within five years.

All foreign manufacturers appear to be well behind U.S. companies in automobile gas-turbine development. Their predictions are also much more conservative, reflecting U.S. views of five or ten years ago.

12.3 Rankine-Cycle Engines

Rankine engines for automobiles are basically of four types: steam with positive-displacement prime mover, steam with turbine prime mover, organic fluid with positive-displacement prime mover, and organic fluid with turbine prime mover. Another broad category of Rankine-cycle engines--those using liquid metals--is not being considered for automobiles.

Steam has been used the longest of any of the available working fluids, and reciprocating prime movers have been used the longest with steam. Other fluids were investigated as the need developed for high power density in the prime mover and for efficient low-temperature cycles. Rankine cycles are subject to optimization for peak efficiency, or reduced size, or reduced cost as a function of fluid and design conditions. Conclusions based on Rankine-cycle optimization and hardware investigations[116,127,145-164] are that steam will lead to the lightest and most efficient simple Rankine engine for automobiles. The efficiency of simple steam cycles is generally limited to about 25% at the best operating conditions; organic Rankine cycles are generally limited to about 20% at the best operating conditions. Thus, organic fluid power plants have boilers a minimum of one quarter larger than equivalent steam plants, and the condensers need to be at least one third bigger. Many organic fluids also have thermodynamic properties that require recuperators to be built into the power plant.

The last two years have seen significant development strides in steam automobile engines. Efficiency has been pushed to near the probable limit for simple steam engines in at least two development programs[147,148], and in one of these development programs, the weight and volume have been brought down to be near competitive with the small engine that it replaced.[147]

Also, the latter engine, described in Table 12.1 (Carter) has demonstrated in actual tests that the 1978 emissions goals have been met with competitive mileage in an auto having an overall weight of 2,750 lbs:

14.9 - MPG
HC - 0.399 g/mi
CO - 1.08 g/mi
NO_x - 0.33 g/mi
WT - 415 lbs

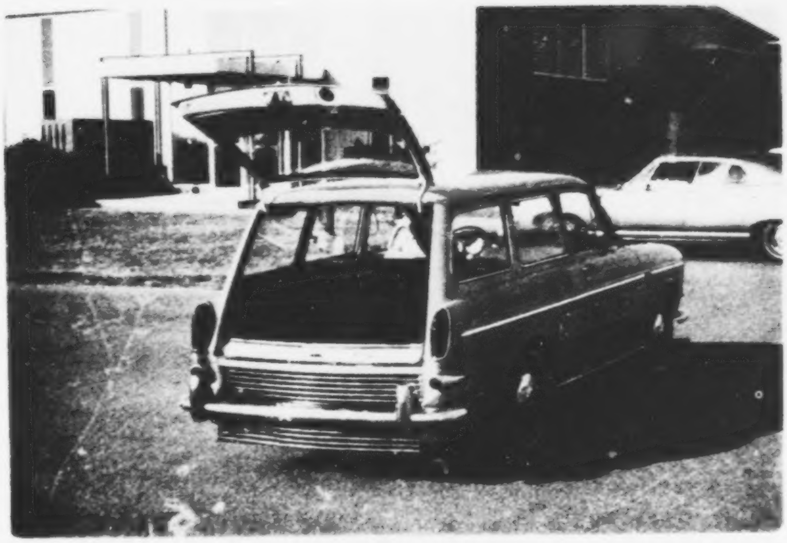
This steam engine has been fitted into a small car (a VW station wagon). Figure 12.1 shows three photographs of the car and components. The engine filled the compartment of the air-cooled SI engine it replaced. In addition, a 35" x 16" x 2½" ram air radiator mounted at the front of the car is satisfactory to 60 mph. A small additional radiator with a fan is mounted in the engine compartment. Fixed cutoff is used. A transmission and variable boiler pressure is used to vary power and torque to the wheels. The boiler pressure is allowed to change in response to power demands. Boiler pressure, water rate, steam temperature, and F/A ratio are all controlled. These innovations lead to simplified controls. The steam is held closely (±15°F) to design temperature at all times to allow the efficiency to be as high as practical over the operating range. The prime mover is a very light piston engine using a unique

TABLE 12.1

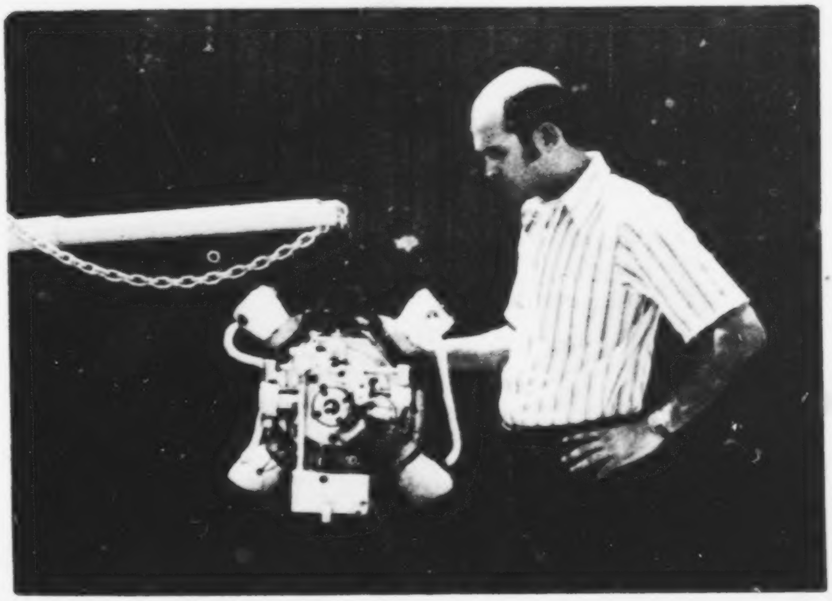
Steam Engine Characteristics

	SPS	SES	Aerojet	Carter	Thermo-Electron
HP	65	150 (gross)	60	90	111.1 (Fluorinol - 85 working fluid)
WGT	940 lb incl. trans.	904 (Projected)	970 lb incl. trans.	417.5 (with front condenser only)	
Fuel Consumption	1.2 lb/HP hr BSFC	10 MG	0.95 BSFC (best)	14.9 mpg FDC* (0.67 BSFC to vehicle dynamometer)	1.3 lb/HP hr BSFC (10.2 mpg-FDC)
Emissions	0.14 HC, 1.2 CO, 0.22 NO_x (Projected)	0.18 HC, 0.43 CO, 0.18 NO_x (Predicted)	0.1 HC, 0.5 CO, 0.17 NO_x (Projected)	0.4 HC, 1.08 CO 0.33 NO_x (Measured at EPA)	0.17 HC, 0.21 CO, 0.275 NO_x (Predicted)
Type	4 Cylinder	4 Cylinder	Turbine	4 Cylinder	4 Cylinder
	Double Acting	Uniflow	(single-stage impulse)	Uniflow	Uniflow
	Compound				
	Hi Pr Bore = 2.125" (2)	3 1/2" bore			4.42" bore
	Lo Pr Bore = 4.25 (2)	3 1/2" stroke			3.00" stroke
	Stroke = 2.125"				
	RPM - 2,400 (max)				
	Valve - variable cutoff - variable timing	variable cutoff variable timing		Fixed cutoff	Variable cutoff
	Monotube boiler - 700 pph	Monotube boiler - 1,200 pph	Monotube boiler - 660 pph	Monotube boiler	
Steam	1,000 psia @ 850 °F	1,000 psia @ 1,000 °F	500 psia @ 1,000 °F	2,000 psia @ 1,000 °F	
Condenser	6 ft^2	6.32 ft^2	3.9 ft^2	3.5 ft^2 (approx) for front condenser	6 ft^2 (approx)

FIGURE 12.1



Rear View of VW with Carter Steam Engine Mounted. The Grill Covers the Boiler Stack and the Rear Condenser.



The Prime Mover Showing the 4 Cylinder.

Continuation of FIGURE 12.1

The Boiler-Burner Assembly.

Source: Reference 147

valving system and uniflow design that lead to high prime-mover efficiency. Extremely good lubrication is achieved which promises to lead to very long prime-mover life. A centrifuge is used to separate oil from the feedwater so that oil will not affect the design or operation of the boiler and condensers. The flow chart for this engine is indicated on Figure 12.2.

The demonstrated starting time to high-speed idle is less than 15 seconds. Time to reach driving power is 27 seconds. The emissions of this engine are not the best that could be expected, but it is not because of the engine design. Rather, the application of principles of combustion design developed in other companies[126,127] could easily reduce the emissions further without affecting the engine in any significant manner.

Good strides were made in the development of another steam engine designed for a larger car.[148] This engine is presently mounted on a dynamometer being readied for simulated driving. Steady-state measurements indicate that the mileage will be near competitive to 1974 vehicles. Very good emission results are also indicated. Table 12.1 describes the SES engine.

A third steam engine presently starting driving tests in a small vehicle (2,500 lb) demonstrates very good emissions in its preliminary tests.[146] Also, mileage appears to be approaching that for emission-controlled, gasoline-engine-powered automobiles of the same weight. Table 12.1 describes the SPS engine and the characteristics of an advanced version as anticipated by SPS.

The Aerojet steam turbine engine built for the "California Clean Car" is also described on Table 12.1. It is not as far along as the others. The Thermo-Electron organic fluid engine is also described on Table 12.1. This engine development was being supported by EPA and Ford. Ford has declined to fund this program further.

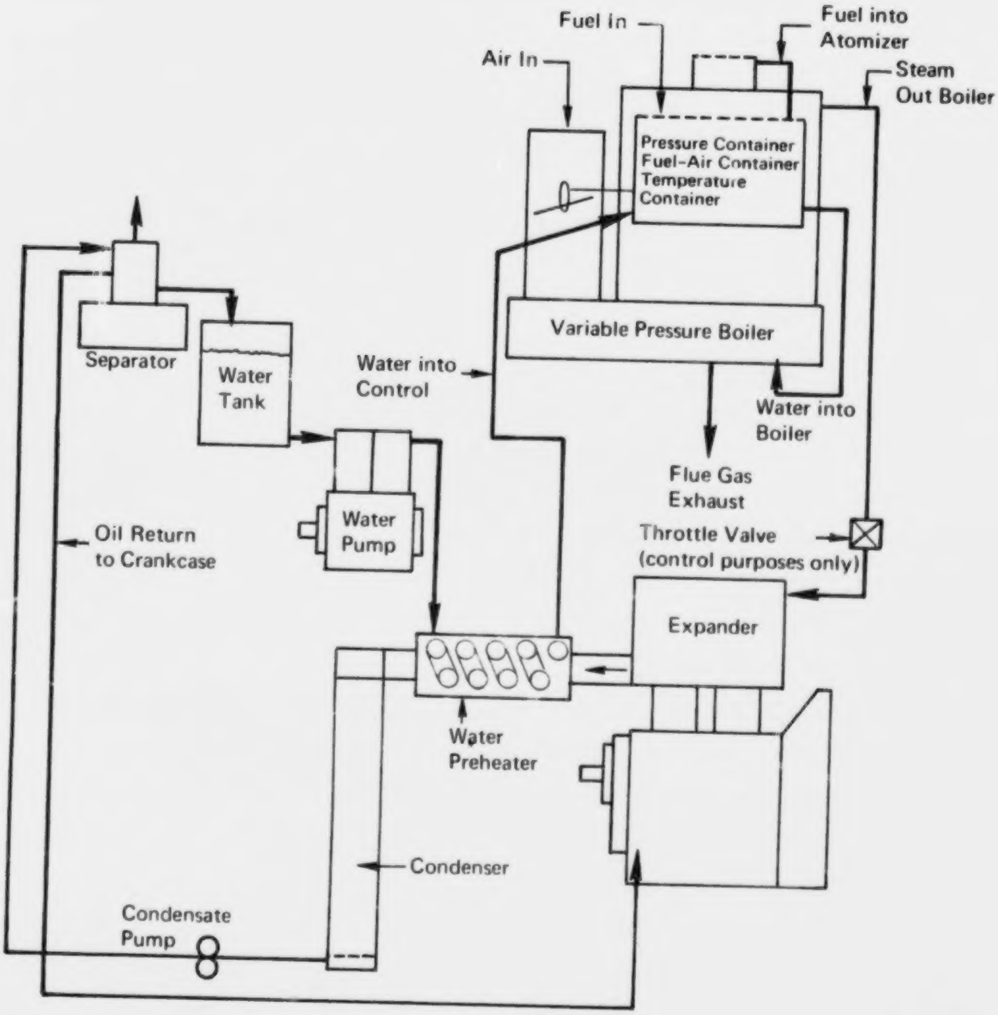

Fuel In
Fuel into Atomizer
Air In
Steam Out Boiler
Pressure Container
Fuel-Air Container
Temperature Container
Variable Pressure Boiler
Separator
Water Tank
Water into Control
Water into Boiler
Flue Gas Exhaust
Water Pump
Oil Return to Crankcase
Throttle Valve (control purposes only)
Expander
Water Preheater
Condenser
Condensate Pump

FIGURE 12.2 Flow Chart.

Source: Reference 147

Cost is the major unknown factor for Rankine engines. With the continued development of manufacturing techniques for boilers, with the use of the simple controls already demonstrated on one of the existing engines,[147] with the use of burners having emissions as low as has been demonstrated already,[126,127,144,148,149] and with the use of the lightweight, simple, well-lubricated prime mover discussed herein,[147] the cost of the engine probably can be brought down to within 50% to 100% of the equivalent pre-control spark-ignition gasoline engine. The prime movers and the accessory drives could, conceivably, be less costly than the equivalent SI engine. The control system demonstrated on the small steam engine in the VW station wagon[147] is the simplest of the Rankine-engine control systems being developed on EPA or State of California contracts.

12.4 Stirling Engines

Basic findings on the Stirling engine as reported in Reference 116 are still valid with some minor modifications. Developments in Stirling engines for automobiles over the last two years[165-168] have centered around installing two experimental versions in marketable auto frames.[165,166] A 175 hp engine has been operating on a dynamometer in the Netherlands and will soon be mounted in a Ford Torino,[165] and a 100 hp engine has powered a Ford Pinto to as high as 65 mph on a flat track.[166] A CVS test simulation indicates emissions of an intermediate-size auto will be:

HC	CO	NO_x	MPG
	grams per mile		
0.20	1.20	0.14	14.7

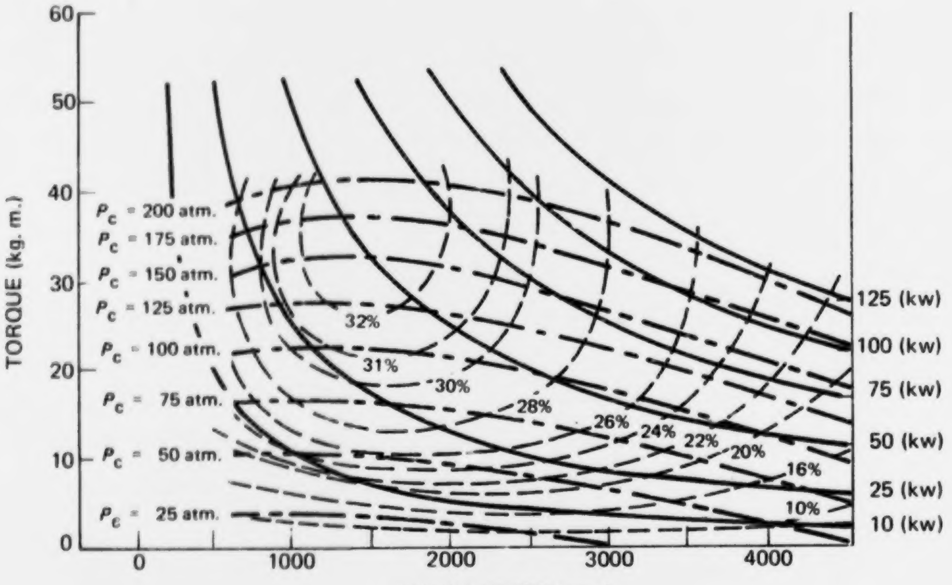
These engines are described in Table 12.2.

TABLE 12.2

Stirling Engine Description

	Philips	United Stirling
HP	170	100
Emissions	0.20 HC, 1.20 CO, 0.14 NO_x	
Type	double acting	double acting
Mechanism	swash plate	V-4, crankshaft
Fluid	hydrogen	hydrogen
Rod Seal	roll sock	rod clearance control
Control	variable mean pressure	variable pressure amplitude
Peak Temperature	1400°F	1400°F
Engine Efficiency (Peak) (see plot below)	32%	25%
Radiator Area		3 ft^2 (3" thick)
Market Goal for Specific Engine	automobile	replaces small diesel

Fuel Economy Map - 4-215 Engine



What is now apparent for Stirling engines is that by tailoring the efficiency slightly, an engine of appropriate power for an existing automobile can be of low enough weight and size, and have sufficient response time to be indistinguishable from gasoline-powered automobiles.[165,166] They are very quiet, the fan and blower noise being the largest contributor to noise; they are very smooth in any workable configuration; they can be made to be very low-emissions engines,[165] they will have low fuel consumption, somewhere close to a nonemission-controlled diesel engine;[165] and they can have exceptional life. On the other hand, the radiator will be harder to fit into a standard automobile.[165,166] Cost and production problems have not been resolved so that the present cost projections show competitive values to diesel, but not to spark-ignition, engines.

Predicted emissions were reported in Reference 116 and still apply. No direct measurements with Stirling engine-equipped cars have been made. However, the emissions should be very low.[169-172]

It is also apparent that the present developers feel that they are at the threshold of the next steps in dramatic improvement.[165-167, 171,173,174] These involve incorporating cheaper materials,[166] improving the power control system to be cheaper and more efficient,[166,167] and more completely integrating the engine into the power train to better meet the driver's demands.[165] They are now better able to cope with optimizing for different applications such as automobile duty, medium duty, and heavy duty. Much remains to be done, and at present rates of spending (about 230-men average load over the world), it will still be three to four years before an acceptable automobile engine will be in existence.

The Stirling engine must still be regarded as an experimental engine for automobiles. While the basic engine is understood, there are a large number of design compromises needed (and unsettled at this time) before the proper development direction can be chosen for particular applications. For instance, it is known that fully metallic engines can be of high efficiency and be quite small and light, but they are expensive. On the other hand, ceramic parts should fit very well into several places of the Stirling engines. This should ultimately lead to inexpensive engines. However, it is not clear which parts will be cost effective to switch to ceramics in mass production, there are no suitable ceramics in mass production for use in such applications, design compromise to use ceramics in such engines is just starting to be a known art, and efficiency versus size of Stirling engines as affected by ceramics is not yet assimilated into the technology. The ceramic work being done on behalf of gas turbines can also be applied to Stirling engines.

a. Stirling engine characteristics -- The objectives for design of a workable Stirling engine beyond that required for any positive displacement engine, primarily are as follows:

- prevent fluid leakage from inside the loop to the outside past the power shaft or rod to keep the engine operable;
- keep all volumes outside the swept volumes as small as possible for highest specific power density;
- minimize pressure losses as the fluid moves back and forth through the heater, regenerator, and cooler for high efficiency and greatest power control range;
- handle as much fluid as possible for best specific power density;
- operate at as high a peak temperature as possible for high efficiency;
- prevent loss of heat from the hot side to the cold side for high efficiency.

These translate into a requirement to use pressurized hydrogen or helium as the working fluid. The classic problems of Stirling engines that also arise from the above list of requirements are:

(1) Heater head:

- Requirements are small volume, large area, low fluid pressure losses, high-temperature materials. Usually forces the use of H_2 or He under high pressure as the working fluid;
- Makes thermal stress a severe problem;
- Makes for high-cost materials and construction technique.

(2) External seal and working fluid diffusion losses:

- Requires either very low loss so one charge lasts a tolerable time without power loss, or requires that the engine be rechargeable.

A third classic problem arises when consideration is given to changing power level:

(3) Power control:

- Requires very rapid method of changing fluid quantity and/or method of changing pressure amplitude variation with a fixed-fluid quantity, to be workable at any engine speed.

All of these problems contribute to the potential cost.

Practically all of the development work going on at this time, beyond making the engines operable in automobiles, is toward technologically suitable solutions of the three major technical problems. Designs which appear suitable for lowered cost are to be developed later from these solutions, so that lower engine costs follow by normal cost reducing methods. One developer is aiming for a car installation that will have run a total of 50,000 miles by December 1975.[165]

It is worth noting that the safety of automobiles has been checked when the hydrogen-working fluid inventory has been lost into the engine compartment. No significant hazard appears to exist.[175]

b. Future possibilities -- It is apparent that much ingenuity has yet to be expended on heater-head design. This thinking is being tempered by the great desire to incorporate ceramics into many parts of the design for very high-performance engines. However, the only ceramic part in any existing automobile-type engines actually running is the rotary air preheater. Time limitations imposed by the automobile company contracting for Stirling engines (Ford) have precluded including extensive development work in ceramics at this time.

The control situation is till pregnant with concepts yet to be tried. The ones being used presently are the variable-mean-pressure type, and the variable-pressure-amplitude type. A simplified variable-amplitude type makes use of fewer valves, with a goal of simplifying to one set of valves for control of all chambers. Philips is reconsidering the variable-pressure control to see if it can be improved. MAN is working on a proprietary system that would bypass the major drawbacks of the variable-amplitude and variable-pressure systems.

Sealing appears to be a tractable problem, more in that it[165] be designed around, as well as partially solved by, direct attack. United Stirling uses a sliding seal with provision for onboard hydrogen makeup. Yearly leakage of a 100 hp engine would be about 4 lb of hydrogen based on their existing data (about 100 refills per year). Philips uses the roll-sock seal for stopping leakage at the seal, and only a yearly check of hydrogen inventory is needed.

The prime movers are all presently piston-type, positive-displacement devices. At least one patent has been issued to an auto company for use of rotary positive-displacement devices. Assuming the mechanical seal problem associated with such configurations can be solved, development could lead to an engine of small overall prime mover size simply because the drive mechanism would now be better incorporated into the package design. The largest part of the prime mover sections of existing Stirling engines is the drive mechanism, be it rhombic drive, connecting rods and drive shaft, or swash plate. A V-4 engine is fitted into the Pinto, and a swash plate engine is being fitted into the Torino (Philips 4-215 engine).

One additional concept worth noting is that one developer thinks highly of a method that incorporates a variable swash plate into the drive design that would essentially eliminate the transmission.[165]

The Stirling engine leads itself well to operation with stored head.[165] The engine can be combined with a thermal storage system (thermal battery) to operate either with sensible heat, heat of fusion, or both, depending on the heat storage material. One research group believes that small cars using Stirling engines with thermal storage units are practical for urban driving.[165] Projected heat storage capacity using fluoride or eutectics of fluorides at 550-860°C range from 0.33 to 0.47 kwhr per kg or 0.72 to 0.93 kwhr/dm. About 35% of this is deliverable as mechanical energy. The delivered energy density would be 50 to 70 whr/lb compared to about 10 to 12 whr/lb for the best existing lead-acid traction batteries. This system would be a competitor to the small battery-powered urban car. The BTU energy balance favors the battery system, but the thermal system can be lighter. Costs of the thermal system are not yet worked out.

12.5 Reciprocating Brayton-Cycle Engines

These engines use reciprocating parts to accomplish compression and expansion. The cycle is basically the same as for gas turbines, and all of the thermodynamic options open to gas turbines are open to reciprocating Brayton engines:

1) Air working fluid, with heat recovery, internal firing
2) Air working fluid, with heat recovery, external firing
3) Air working fluid, no heat recovery, internal firing
4) Air working fluid, with heat recovery, external firing
5) H_2 or He working fluid, with heat recovery, external firing.

Only the last one has been studied experimentally in the last few years; types 3 and 4 have been in the patent literature for decades. Thermodynamic performance demonstrated to date on Type 5 is quite poor (about 12%), but an efficiency on the order of 27%-30% should be attainable using the same materials, etc., that would be used in the equivalent Stirling engine.[176,177] The Brayton engine has the advantage that pressure losses due to small heat exchangers can be avoided and that power density is not sensitive to external volumes. But, it has the disadvantage that one set of hot valves is needed. Otherwise, the Stirling engine and externally fired Brayton engine with H_2 or He working fluid have many of the same characteristics. The Brayton engine has some design flexibility advantage over the Stirling engine in that more freedom on pressure ratios exists. This may be an academic advantage, however, since present Stirling volume ratios appear near optimum. Because the Brayton engine relies on isentropic processes for compression and expansion instead of isothermal heat transfer processes (as in Stirling), and because the Brayton engine uses a recuperator rather than a regenerator (as in the Stirling) for cycle heat recovery, the Brayton engine thermodynamic efficiency runs somewhat lower than for a Stirling engine operating between the same temperatures. A recuperator transfers heat between two fluid streams with an effectiveness of 85% or less except where large volumes can be tolerated. A regenerator collects heat from a hot fluid, stores it, and later transfers it to a colder fluid with effectiveness that can range up to 98%. The meaning of these tradeoffs is that the Stirling engine should be able to attain higher efficiency at the same or less cost, but that the design problems are more difficult than for the reciprocating Brayton cycle.

The use of air in reciprocating Brayton engines is possible from a practical point of view because the heat exchangers can be designed for air without compromising the engine power density and efficiency. The operating conditions of the engine are limited, however, by the action of hot air on the materials of construction. Whether internally or externally fired the same limitations apply. Internal firing has the advantage of reducing heater size and cost, but could lead to poor emissions if the performance is to be satisfactory. External firing has the same limitations as for the H_2 or He engines.

If the problems associated with achieving a suitable Stirling engine design of the conventional type prove insurmountable from a cost point of view, then the reciprocating, valved, Brayton engines will be worthy of further consideration.

12.6 Flywheel Systems

Flywheels of new designs offer the possibility of very high energy storage density.[178,179] A flywheel with sufficient specific storage capacity to drive a car in a conventional way requires a sophisticated design, a vacuum chamber to run in, and a seal and vacuum pump for maintaining the vacuum. The drive requires an alternator with a variable-speed, variable-frequency type converter or variable-speed, constant-frequency converter with additional control for electrical drive or an infinitely variable transmission. Thus, for the electrical drive, the drive system alone will cost one and one-half to two times the engine and transmission it replaces. This is the same as for battery-drive vehicles.[174] In addition, there is the cost of the flywheel assembly. Unlike battery drives, there is little probability that the flywheel could be an easily replaceable unit for quick change at a service station. Thus, the flywheel has to be considered part of the automobile's first cost to the customer rather than an operating cost as with gasoline or easily replaceable batteries. Flywheels and their vacuum chambers suitable for 200-250 mile range will probably cost on the order of an uncontrolled engine, sized for similar service, based on estimates available in preliminary studies.[178] Special transmissions, vacuum devices, chargers and controls, or electrical drives are additional. Also, the demonstration of such a system in an automobile, irrespective of cost, is several years away.

Use of an infinitely variable transmission would bring the power plant cost down to that of the flywheel assembly, the transmission, a gearbox, and a charging motor. The total cost may conceivably be brought down to one and one-half to two times that of uncontrolled spark-ignition engines if the flywheel assembly can really be made to cost the same as an uncontrolled spark-ignition engine. Demonstration of this cost probability and demonstration of the flywheel system in a vehicle would be required before it could be considered seriously as an automobile drive. The safety aspects of flywheel operation will also have to be demonstrated in a vehicle, although the frangible flywheel using glass fibers has been shown to disintegrate effectively without problem when malfunctions occurred. The emissions would take on the nature of the central powerplant, similar to battery systems.

12.7 Electrically Driven Vehicles

a. Introduction -- The assessment of the performance of present and anticipated electrically driven vehicles as presented in Reference 116 requires additions and corrections in the light of new developments. Recent vehicle systems studies,[180-186] battery and vehicle test programs[186-189] and advancements in battery technology[190-194] allow a more concrete appraisal of future vehicle capabilities. The gasoline fuel shortage experienced during the past year, as well as the rapidly rising cost of crude oil, have provided a powerful spur for seeking alternative power sources for transportation. Electric vehicles, at least on superficial examination, seem to offer potentially significant fuel savings. (183,188,195,196)

It is well understood, of course, that the use of electrical drives in vehicles entirely removes the polluting source from the vehicle and transfers it to the central power plant. The cleaning up of emissions from power plants need not be considered here; this problem is already receiving intensive attention. The additional power demand by electric vehicles seems not serious considering the unavoidable low rate at which such vehicles could be added to the present transportation scheme. For instance, if all driving in the USA were by electric cars (approximately 10^{12} miles per year) requiring about 0.4 kwhr/mi, the nighttime average electrical generating capacity required for charging would be about 150,000 megawatts. This is not much greater than the present nighttime excess generating capacity in the United States. Gradual introduction of electrical vehicles should result in demands less than the excess capacity.

b. Batteries -- Results of recent test programs and of developmental efforts lead to the following assessment of present and future capabilities of batteries:

(1) The lead-acid battery is the only currently available electric sotrage system for automotive traction with a reasonable cycle life and cost per unit energy stored. Its key limitation, energy storage density, can be improved sufficient (from 10 to 12 whr/lb to about 13 to 15 whr/lb) but this is not to permit application beyond marginal-performance urban vehicles, delivery vans and busses.[197] Even if the cycle life were to be extended to 1,000 deep cycles, the amortization of the battery over its lifetime will lead to a cost of the battery alone amounting to 3-5 cents per kwh delivered.[180-182,184]

(2) Other battery systems with "intermediate" performance will very likely become available within the next five years;[187,190] see Table 12.3. Although these promise to provide two-to-threefold improvement in energy density, relative to the lead-acid battery, it is unlikely that their cycle life can be sufficiently improved to provide economically attractive energy storage cost. However, because the future Zn-NiOOH system may have good power capability, its application in electric vehicles and perhaps in gasoline-electric or battery-battery electric hybrids deserves consideration.

(3) Recent advancements in the technology of the solid electrolyte (beta-alumina), as well as in other critical areas affecting the feasibility of alkali metal sulfur systems, increase confidence in the eventual technological feasibility of high-energy, high-power density battery systems.[182,192,195] Prototype producing and testing programs should provide definitive answers in the next three to five years as to whether the alkali-metal-sulfur batteries can provide an economically viable solution to the energy storage needs of electric vehicles. Indications at present (Table 12.3) are that battery amortization costs may achieve a level below 1/cent/mile. Current work on the feasibility of battery schemes employing alkali-metal

TABLE 12.3

Batteries for Electrically Driven Vehicles

System	Theoretical	Best Present Performance					Anticipated Performance					
	whr/kg	wh/kg	peak w/kg	cycle life	operating time,year	cost $/kwh	wh/kg	peak w/kg	cycle life	operating time,year	cost $/kwh	year
$Pb/H_2SO_4/PbO_2$*	175	22 to 26	100 to 200	300 to 1,000	1.5 to 2	30 to 50	28 to 33	100 to 200	500 to 1,000	3	40 to 50	1976/ to 1978
Zn/KOH/NiOOH	326	55	100** to 200	200	1	100	30** to 35	100** to 200	500**	3	30** to (1) 50	1978*/ to 1980
$Zn/ZnCl_2/Cl_2.6H_2O$	465	70	50	10	?	?	110	100	500	3	50	1980
Fe/KOH/NiOOH	267	36	35	2,000	3	50	44	100** to 200	500	5	50 (1)	1978
H_2/KOH/NiOOH	381	65	40	1,000	1	?	80	100	3,000	3	100 (1)	1980
Li/LiCl.KCl/S	2,500	150	150	100	0.2	?	330	200	1,000	3	20 50	
$Li_2Al/LiCl.KCl/FeS_2$	790	120	120	200	0.5	?	200	200	1,000	3	20 50	1980
Na B-Alumina or Na-glass S	760	90	150	1,500	1	?	180	200	1,000	3	20 50	

*Data and estimates pertain to deep (70-80%) discharge at 1-3 hr rate. Range of numbers refer to range of usage.

**Ranges refer to uncertainty.

(1) With metal recovery accounted for.

negative electrodes at lower temperatures (in the range of 200°C) shows good initial promise.[190] Significant advantages in cell construction technology and cost may be derived from operation at this lower temperature level. Production of significant numbers of electric vehicles based on alkali metal batteries cannot be expected before 1985 at best.

c. Electric drive train -- There are a number of viable alternatives for motor and switch-gear systems suitable for use in electric vehicles. Systems studies and experimental test programs indicate that electric systems which have favorable torque and speed-control characteristics combined with high efficiency will have initial costs (excluding the battery) comparable to or higher than the present-day drive train of gasoline-powered automobiles.[182,183,185] Weight of the drive train depends greatly on the system, although the order of magnitude appears to be about 1½ to 2 kg/hp. The VW van being worked on at DAUG and VW suffers a weight penalty of about 100 to 200 lbs for an electric vehicle without batteries compared to a gasoline-engine-powered van. Motor and switch gear possessing optimal characteristics for electrics are not yet fully developed. The drive train aspect of electric vehicles, however, does not appear to present the limiting factor in the eventual realization of efficiency and economically attractive electrical vehicles.

d. Hybrids -- Recent tests by EPA on a gasoline-engine-battery-hybrid vehicle (Petro Electric)[198] demonstrated with a 4,000 lb vehicle the following emissions and fuel economy over the Federal Driving Cycle:

HC	CO	NO_x	MPG (avg)	MPG (engine off at idle)
(grams per mile)				
0.45	2.08	0.90-1.14	10.4	12.4

A Wankel engine and lead-acid batteries were used. The driveability of this vehicle was acceptable. Further improvements in meeting emissions standards and in gas economy can be expected by using a conventional small gasoline engine rather than the Wankel employed in this test vehicle. Other test programs involving hybrids[185,187] have not produced as yet sufficient data on emissions characteristics and on energy efficiency to make meaningful conclusions possible. Because hybrid drive systems are more complex than either of the derivative systems, the initial cost of the vehicle promises to be high. However, the anticipated longer cycle life of advanced battery systems may provide a basis for favorable vehicle cost per mile.

Tests conducted at EPA in October-November of 1974[*] with the Petro-Electric vehicle yielded the following results:

HC	0.38 g/mi
CO	2.41 g/mi
NO_x	0.76 g/mi
MPG	9 urban
	16 highway

These results were obtained at 4,000 lb inertia weight and with a high rear-end ratio. The mileage is for the battery recharged to its starting level. A rotary engine is used in conjunction with the electric system. Using an EPA determination factor for a rear-end ratio one half that used in the test, and the improved economy of a piston engine versus a rotary engine, the predicted urban mileage would be $1.35 \times 2^{.6} \times$ measured value = 17.9 mpg. Past EPA tests on the Petro-Electric vehicle have indicated highway mileage nearly double the urban mileage.

The electric system includes a set of starter, light, and ignition (SLI) batteries having 90 amp hours of storage. Discharge is only by 2 amp hours before recharging starts and does not normally exceed 6 amp hours during operation. Also included is an electric motor rated at 10 hp continuous, or 20 hp for one minute, or 40 hp for acceleration.

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[*] Telephone call from H. Wouk, President, Petro-Electric Motors, Ltd. to J. Bjerklie, December 12, 1974.

Costs have been resolved except for the batteries and the motor in large production. Including these items, the purchase cost of the Petro-Electric vehicle would be between 10%-20% higher than the equivalent gasoline-engine-powered vehicle for the same emissions and performance. (Note: This information was approved and added to the consultant report December 13, 1974.)

(e) Power demand -- Most recent estimates on power demand[181,195, 196,199] to be created by electric vehicles tend to confirm earlier estimates according to which the availability of centrally generated electrical power and of distribution network is not likely to present a constraint on the introduction of even a moderately large population (i.e., addition of 1-2 million vehicles/year) of such vehicles. Because of the load leveling potential of electric vehicles (i.e., charging during off-peak periods), economical benefits may be derived from such a power demand resulting in lowering the average cost of power.[196] In the planning of central load leveling facilities, it would be of distinct advantage to be able to rely on competent estimates regarding the expected penetration of electric vehicles in the transportation system.

(f) Energy economy -- The energy requirement of an electrically driven vehicle compared to that of a gasoline-driven car has been estimated by a variety of methods.[180-184,188,195,196,199] Because of the paucity of road-test data on electrics, a fully reliable comparison is still not available. One of the key difficulties in making a valid comparison between even the smallest gasoline-driven automobile and an electric vehicle available for road tests is that at present the only battery system (i.e., the lead acid) at all suitable for vehicular application provides extremely limited power and range. Once we put together on paper an electric car with performance similar to at least the smallest cars on the road today (Honda, Pinto, Vega, VW, etc.), we must anticipate performance of batteries which are not yet available.

Keeping the foregoing remarks in mind, recent system-performance studies provide the following estimates:

The energy requirements per mile of lead-acid-driven electrics using current technology for the frame and driving train are comparable to the subcompacts on the road today[182,184] (0.25 to 0.5 kwhr/mile). This disappointing performance results from the very high weight of the battery required for even a marginal vehicle range and marginal acceleration/hill-climbing capability.

The energy requirements per mile for cars powered by "intermediate"-type batteries (e.g., NiOOH, $Ni-H_2$) can be expected to be comparable to those of current subcompacts. The higher energy density and power density of these intermediate battery types will considerably reduce vehicle weight.

The energy requirement of electrics using alkali metal-sulfur batteries, with energy and power densities in the range of 100 kwh/lb and 100 wh/lb, respectively, should be somewhat lower than present-day, gasoline-driven vehicles (compacts) with comparable performance.

It is worthwhile to compare the amount of raw fuel required per mile to drive electric and heat-engine-powered vehicles. From the results indicated above, it can be assumed that electric cars competitive to subcompact gasoline cars will require an average of about 0.35 kwhr/mile. On the other hand, a family-size car averaging 15 mi/gal requires about 0.45 kwhr/mile. This would correspond to an intermediate-size car powered by a Stirling engine. The conversion of raw fuel to drive-shaft power would be approximately as follows:

		Electric Car	Heat Engine
Fuel processing efficiency	=	.9	.9
Power plant efficiency	=	.32	.19
Trnasmission line efficiency	=	.91	
Battery charge/discharge efficiency	=	.7	
Motor/control efficiency	=	.8	
Transmission and gear	=	____	.9
Overall efficiency	=	.146	.154

Adjusting for the difference in kwhr/mile required by the two modes of transport, the ratio of electric vehicle to heat engine vehicle fossil fuel requirements is 0.82. This ratio is low enough to induce some interest in electric vehicles at the present time.

If the transportable fuel of the future requires more thermal or electrical processing than indicated above, the energy ratio will drop further since the fuel processing efficiency for electrical generating plants need not change so long as fossil fuels are used. For instance, if hydrogen were to be required for automobile fuel in the future, and if it were to be generated electrolytically, the ratio will be under 0.6. This should include higher interest in electric cars if energy remains a potential major national problem.

g. Summary:

(1) There are no alternative engines that can be available in mass production for automobiles of standard size and performance before the 1980's.

(2) All of the alternative heat engines can be made to meet the 1978 emissions standards, with Stirling engines and steam engines able to do so most easily and with least controversy on interpretation.

(3) Present gas turbines show poor fuel economy in urban driving, but could be made to show good characteristics for touring-type driving.

(4) High-temperature gas turbines with ceramic components for high-temperature portions of the engine should be technically competitive with spark-ignition engines over 50 hp and should demonstrate excellent fuel economy over a Federal Driving Cycle. Their economic competitiveness is not now clear.

(5) Stirling engines should ultimately be technically competitive with spark-ignition engines over the power spectrum used by conventional automobiles. It is a necessary, but not sufficient, condition to achieve a control system and heater head that can be made at a considerably lower cost than at present to be economically competitive.

(6) Steam engines have been shown to be technically suitable as an exhaust-clean engine for powering lightweight cars.

(7) None of the alternative heat engines have been shown to be suitable in the hands of the public, although gas turbines come closet to having done so.

(8) None of the alternative heat engines have been shown conclusively to have a suitable cost structure for use in conventional automobiles.

(9) Light vehicles powered by efficient, externally heated engines (such as Stirling), using heat stored in a thermal storage system, are being studied for their suitability as an urban vehicle. The system has not yet been shown to be economically competitive.

(10) Heat engine-battery hybrids have beem demonstrated successfully at the EPA to achieve on the Federal Driving Cycle; HC = 0.45 g/mi, CO = 2.08 g/mi and NO_x = 0.9 to 1.14 g/mi, and to negotiate the Federal Driving Cycle successfully.

(11) Flywheel systems have not been shown to be competitive with spark-ignition engines costwise, technically, or for overall emissions.

(12) Based on present technology, it is feasible to manufacture electrically driven personal vehicles for restriced (low range and power) urban use. These vehicles, even when equipped with the best, currently available, lead-acid storage batteries, will have significantly higher initial cost and vehicle cost per mile than today's gasoline-driven subcompacts with no improvement in overall energy efficiency.

(13) Active development programs exist for battery-powered delivery vans and urbans busses. Their duty cycle offers an opportunity that is thought may prove economically viable for the introduction of electric drives and lead-acid batteries.

(14) By substantially increasing the cycle life of lead-acid batteries, major improvements in energy economy and vehicle cost per mile may be achieved by decreasing the cost per mile of the battery. Significant improvement in range is not likely to be achieved with the lead-acid battery.

(15) Other battery types currently in advanced development stage (e.g., Zn-NiOOH, H_2-NiOOH) may be expected within five years to provide approximately twice as high specific energy (range) and significantly improved power capability compared to the current best lead-acid system.

(16) The high energy and power density alkali metal-sulfur batteries currently under development show good promise and should reach advanced testing stage in two to three years.

(17) In view of the strong likelihood for a gradual shift toward coal-nuclear-geothermal and, perhaps, solar primary energy sources, there are incentives for the development of advanced storage batteries for electrically driven vehicles.

(18) A summary of fuel economy data for alternative engines is given in Figure 12.3.

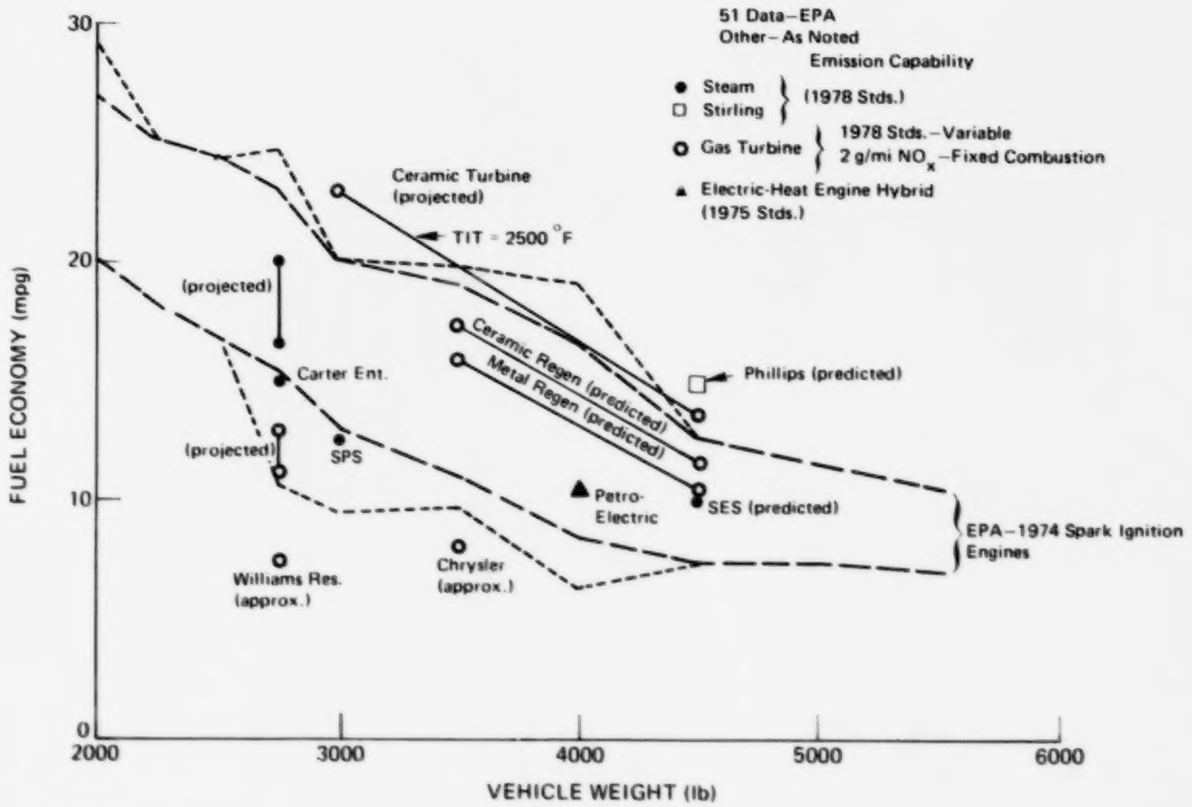

FIGURE 12.3 Fuel Economy - Alternative Engines. All Data Are Measured Except: Predicted from Dynamometer and Projected from Extrapolation.

13. ALTERNATIVE FUELS

13.1 Introduction

The recent gasoline shortage in the United States has served to emphasize the critical dependence of our transportation system on a readily available and abundant supply of gasoline. Nearly all present-day transportation systems are powered by petroleum-derived fuels. Petroleum currently supplies almost 50% of U.S. energy needs with the transportation sector, in turn, consuming about half the petroleum. Gasoline for automotive consumption represents approximately 75% of this transportation fuel demand, or nearly 20% of the total U.S. energy usage. It is not surprising then that alternative fuels for automobiles are of great current interest in view of government plans to try to reduce the petroleum dependency of the United States.

The subject of alternative fuels interacts in various ways with the current Committee on Motor Vehicles study. First, and most obvious, the types of fuels available can potentially have a significant effect on the performance, efficiency and emissions characteristics of the various automotive power sources being considered. Thus, an attempt is made here to identify the alternative fuels that may become available in the future.

The type of fuels which will be available will, in turn, depend upon the future energy supply spectrum. National policy concerning this future energy mix is currently being formulated in terms of research and development goals and budgets for nuclear, coal, oil shale and other energy sources. The identification of those synthetic fuels which are most attractive for automotive applications should serve as input to these energy policy decisions. Those alternative fuels particularly advantageous for automotive use are identified and discussed in the present study.

Another motivation for considering alternative fuels is the interaction between alternative fuels and alternative power plants.

Many of the alternative power plants are chacterized by continuous-combustion systems with relatively little fuel sensitivity, while other power plants may require fuels with specific octane or cetane ratings. The future availability of fuels of various types may then affect decisions regarding production of automotive power plants of a given design. The spectrum of available fuels may also affect the design of conventional spark-ignited engines, stratified-charge engines and diesel engines, and discussion of alternative fuels for these engines is included here.

For the present study, alternative fuels are defined as those fuels not derived from the normal petroleum base. Fuels which are derived from such sources as coal, oil shale, natural gas or nuclear energy resources are considered. Except for direct use of natural gas, all of these energy sources require further synthesis or conversion to obtain a form suitable for automotive application. Hence, the term "synthetic fuel" can also be used to characterize fuels from these resources. In the cases where the alternative fuels are synthetic gasoline or synthetic distillates, the discussion includes information on their potential availability and cost, but does not dwell on their application to conventional vehicles.

The objective of this study is to assess the potential for alternative automotive fuels from the standpoint of energy supply and cost, vehicle efficiency, performance and emissions. Also, where possible, an attempt is made to assess the time frame for availability of the various synthetic fuels.

A summary of synthetic fuel cost and supply data based on presently available estimates is given in the next section. Subsequent sections contain detailed assessments of the prime non-conventional synthetic fuel candidates: hydrogen, methanol and gasoline-methanol blends. A discussion of systems employing reformed fuel is also included because these systems have potential fuel economy and emissions advantages.

13.2 Candidates, Costs and Time Scales

Given the energy resource picture for the United States and the projections for rates of energy usage, it quickly becomes apparent that a heavy reliance on imported petroleum can only be avoided by exploitation of non-petroleum, domestic energy resources. A typical petroleum demand projection is shown in Figure 13.1, taken from Reference 200 and indicates that petroleum demand due to transportation alone will outstrip domestic supplies by 1980.

It is of interest then to consider the possibility of using non-petroleum energy resources for synthetic fuel production for automotive transportation needs. The available major domestic energy resources in this category include coal, oil shale and nuclear supplies. Solar and geothermal energy resources may also enter the picture, but detailed analyses of their application to synthetic fuel production are not readily available. Foreign natural gas is the other non-petroleum resource considered here. Given these energy resources, fuel candidates, costs and availability are analyzed in this section.

Recent studies performed for the Environmental Protection Agency by the Institute of Gas Technology (IGT) [201,202] and Exxon Research and Engineering[203] have identified alternative automotive fuel candidates and costs based on use of domestic resources. While both studies started with a long list of possible fuels, many were immediately eliminated for obvious hazard, availability, storability or cost problems. The IGT study provided cost data for a number of fuels, while the Exxon analysis eliminated all but a few candidates for practical reasons before final cost data was completed. Cost estimates from these studies in 1973 dollars per million Btu at the pump are shown in Tables 13.1a and 13.1b. Current gasoline prices (without taxes) are equivalent to about $\$3.50/10^6$ Btu.

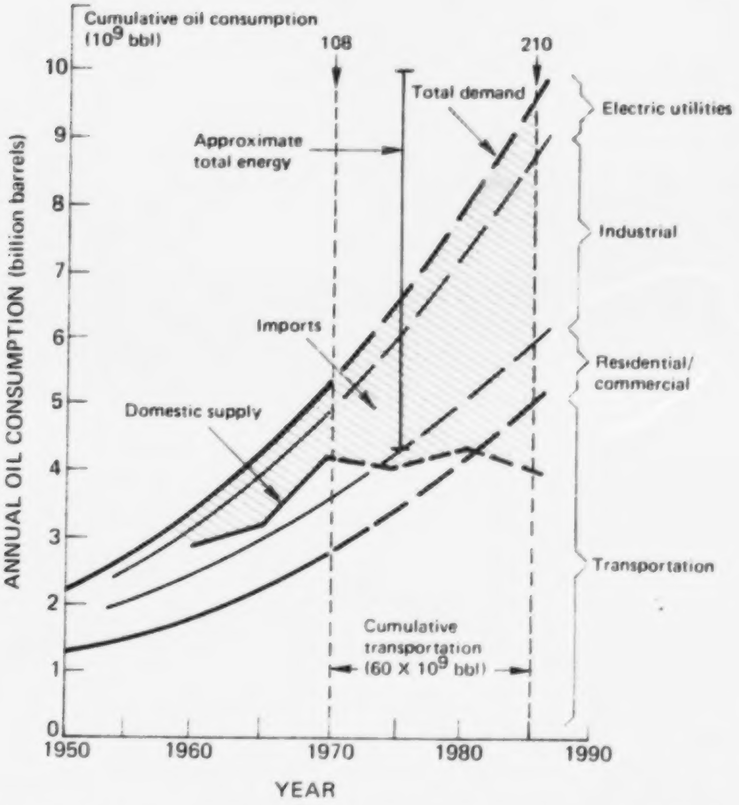

FIGURE 13.1 U.S. Petroleum Supply and Demand (Including Natural Gas Liquids).

Source: Reference 200

TABLE 13.1a

Cost of Alternative Fuels

Resource Base	Synthetic Fuel	Cost at Pump $\$10/^{6}$ Btu
Coal	Gasoline	3.00 (+1.70)
	Distillate	2.65 *(+1.40)
	Methanol	2.85 (+2.38)
	Liquid SNG	3.60 (+0.94)
	Liquid H_2	5.65
	H_2-Hydride	3.55
*Co-production (50-50) gasoline and distillate		
Oil Shale	Gasoline	2.95 (+1.20)
	Distillate	2.50 (+1.20)
Nuclear Energy	Electrolytic H_2	
	Liquid H_2	7.60
	H_2-Hydride	5.50
	Thermochemical H_2	
	Liquid H_2	6.10
	H_2-Hydride	4.00

Assumptions:

Costs are in late 1973 dollars, for investor financing with approximately 10% DCF. Capital and operating costs were based on published (late 1960's) costs and are probably somewhat optimistic.

Note:

IGT has recently completed more detailed cost analyses for several of the above fuels. These costs were based on full-size plants reflecting maximum economy of scale. Costs included total plant investment, 10% overhead, 15% contingency, interest during construction, start-up costs and operating costs. Substnatially greater production costs were obtained in this analysis. Increases are shown in the figures in parenthesis above (Ref. 2a).

REF 201

TABLE 13.1b

Cost of Alternative Fuels

Resource Base	Synthetic Fuel	Cost at Pump $\$/10^6$ Btu
Coal	Gasoline	3.35
	Distillate*	2.75
	Methanol	3.85
Oil Shale	Gasoline	2.65
	Distillate*	2.05

*Produced as coproduct with gasoline

Assumptions:

1973 Dollars, 10% DCF Return.

REF 203

Jaffe[204] et al. have estimated selling prices for methanol from coal for a number of coal sources and gasification processes. Their results for methanol from coal, without coproduct, are in the range \$250-\$3.00/10^6 Btu for investor financing at 12% DCF. Transportation charges (about \$1.50) would have to be added to these costs to arrive at a cost.

Other estimates for methanol costs are also available. Vulcan-Cincinnati Company estimates that methyl fuel (methanol with small amounts of high alcohols) could be produced from coal for \$1.02/10^6 Btu.[205] Dutkiewicz[206] estimates that methanol produced from natural gas in the Middle East could be brought to the United States for \$1.05/10^6 Btu. Transmission and distribution would add about \$1.50 to these costs[202,203] for an estimated total delivered methanol cost of \$2.50/10^6 Btu.

The time frame for availability of the various synthetic fuels is also of interest. The Office of Coal Research (OCR) estimates that the data necessary for design of a commerical-size plant for substitute natural gas (SNG) production from coal will be available by 1980.[207] However, due to increasing demand for natural gas in present markets, it is unlikely that SNG from coal would be available for automotive use any time before 2000, if then.[202] The state of the art in coal liquefaction in the United States is not as advanced as coal gasification. OCR estimates that the technology for pilot and demonstration plants for liquid fuels from coal should become available in the early 1980's.[207] Allowing time for demonstration plant operation, synthetic liquids (gasoline and distillates) from coal will probably not be available in substantial quantity before the late 1980's.

Production of methanol or methane and methanol is another possible option for coal gasification plants. This would involve first producing synthesis gas (containing large quantities of CO and H_2) in much the same way as in SNG production. Methanol would then be produced from the synthesis gas by commercially available catalytic conversion methods. This would have the advantage of producing a liquid fuel from coal while requiring only gasification technology rather than direct liquefaction technology. An early 1980's time frame is then probably appropriate for methanol from coal. Mills and Harney[208] have discussed methanol production from coal and suggest a production cost in the range of $\$1.00$-$\$1.20/10^6$ Btu. Methanol is currently produced via steam reforming of natural gas, and it has been suggested that natural gas from the Middle East be converted to methanol for shipment to the United States.[206] No further technological development would be required here.

Production of gasoline and distillates from oil shale is also an attractive low-cost option (Tables 13.1a, 13.1b). Oil shale leases have recently been granted and processing plants are being designed. The technology for retorting the shale oil to a synthetic crude oil is known, and a few plants based on surface mining of shale will probably be in operation in the early 1980's.[209] The major limitations here are not technology development or processing costs, but enviornmental problems and water shortages which may limit the scale of operation.

Cost estimates for either liquid or metal hydride forms of hydrogen are relatively high (Tables 13.1a, 13.1b) due to inefficiencies in the electrolytic or thermochemical production methods and the additional costs for either liquefaction or hydride formation. Electrolytic hydrogen production followed by liquefaction is a currently available technology, and development of more efficient electrolyzers continues. Thermochemical hydrogen production and metal hydride storage systems are still in the early stages of development and may not be commercially available until the late 1980's. Although production of gaseous hydrogen may be relatively cheap (Tables 13.1a, 13.1b), its low density eliminates it as an automotive fuel.

Given the above cost and availability estimates, we identify the most attractive alternative fuels as follows. Some quantities of methanol from either coal gasification or foreign natural gas will probably be available as early as 1980. If system studies indicate that this fuel should be used in the transportation sector, then use of gasoline-methanol blends for automobiles would be an early application. Larger-scale production of methanol in the late 1980's could result in some use of methanol itself as an automotive fuel. The most likely synthetic fuels for the late 1980's and the 1990's appear to be synthetic gasoline and distillates from coal or oil shale resources. Hydrogen may appear as an automotive fuel, but will probably not be widely used before 2000.

A more detailed discussion of the automotive application of several synthetic fuels is included in the following subsections. No further discussion of synthetic gasoline or distillates is given since these would be essentially the same as presently available fuels. Systems which include on-board reformers are also discussed since, even though the vehicle may be fueled with conventional fuels, the engine will operate with some portion of synthesized fuel.

13.3 Hydrogen

During the past few years, hydrogen has received a great deal of attention as a potential energy carrier of the future. Its major attractions include the absence of carbon in the fuel and the vast availability of hydrogen in water. The prime energy sources in a hydrogen-energy economy would be nuclear, solar or geothermal, and the hydrogen produced from these resources would serve the need for an easily transmitted, storable, portable energy carrier. While the beginning of any conversion to a hydrogen economy appears to be at least 25 years away, many investigations of hydrogen's potential as an automotive fuel have already been carried out. The present section discusses vehicular storage problems and potential automotive engine performance and emissions with hydrogen as a fuel.

Assuming widespread production and distribution of hydrogen as a multi-purpose energy carrier, the major problem accompanying its use as a vehicular fuel is the requirement for on-board fuel storage. The low volumetric energy density of hydrogen eliminates gaseous storage and leaves cryogenic liquid hydrogen or solid metal hydride compounds as possible storage modes. Cryogenic hydrogen storage systems would occupy four to five times the volume of present gasoline tanks, and would require a vacuum-jacketed, specially insulted tank to minimize boil-off losses.[200,213] At the present time, such cryogenic storage systems would be quite costly, although large-scale mass production should reduce costs considerably. All of this supposes a method for liquid-hydrogen delivery to individual vehicles. Gaseous pipelines to service stations with liquefaction equipment or widespread distribution of liquid hydrogen would be required.

Metal hydride storage involves the formation of a solid phase metal-hydrogen chemical compound, e.g., $Mg\ H_2$. Although the weight fraction of hydrogen in these compounds is usually less than 5%, quite high hydrogen storage densities can be achieved by virtue of the solid phase. Magnesium or magnesium-nickel hydride systems are estimated to weigh 600-700 lb to give an energy storage equivalent to a standard gasoline tank[200,210] Iron-titanium or magnesium-iron-titanium hydrides have operating temperatures and hydrogen evolution rates more suitable for vehicular application, but would weigh as much as 1,500 lb.[211] The metal hydride decomposition to give the hydrogen fuel is an endothermic chemical reaction, and the vehicular system would therefore require a provision for cold start-up and exhaust-heat recycle to deliver the fuel to the engine. Some demonstration hydride storage systems have been built and laboratory research programs continue to investigate lighter-weight metal hydride compounds.[212] Much of this research is being carried out at Brookhaven National Laboratory. Widespread use of metal hydride storage would, of course, require a metal readily available in large quantities. Hydrides can be recharged from a pressurized gaseous hydrogen supply so that cryogenic distribution is not required.

While the vehicular storage of hydrogen requires some research and development before widespread practical application is possible, the efficient use of hydrogen in the vehicle power plant can be accomplished with present-day technology. Hydrogen-air mixtures are easily ignited and burn rapidly over a wide range of mixture ratios. Alternative engines which employ continuous combustion systems (Brayton, Rankine or Stirling engines) are thus readily adaptable to hydrogen fuel. The primary combustion zone in these systems can be operated much leaner than with hydrocarbon fuels so that low nitric oxide emissions are easily attained.

Application of hydrogen to spark-ignited, reciprocating engines requires some engine modifications for proper operation and some gain in engine efficiency is possible. We mention here some recent experimental results on the performance, emissions and special problems of hydrogen-fueled, spark-ignited, reciprocating engines.

Since hydrogen-air mixtures require only one tenth the ignition energy of gasoline-air mixtures, preignition and flashback can be problems when operating with hydrogen. Both intake water injection and exhaust gas recirculation (EGR) have been used to eliminate these problems.[215,217] Both of these techniques also reduce nitric oxide emissions and maximum engine power, and water has the additional complication of requiring a storage tank which must be freeze protected. Direct cylinder induction[218] and high-pressure, direct-cylinder fuel injection[214,219] have also been used to eliminate flashback and preignition problems. Direct injection has a supercharging effect and can increase power output 20% over a carbureted system.

Engine knock is also a problem with hydrogen-fueled reciprocating engines due to the high flame speeds of hydrogen air mixtures. To avoid this, it has been found necessary to operate with mixtures much leaner than stoichiometric or to employ EGR. Both of these techniques result in some loss in maximum engine power.

A notable advantage of operation with hydrogen is the efficiency gain attained through quality regulation of the engine power compared with controlling output by throttling. This is possible because of the extremely wide flammability limits of hydrogen-air mixtures and has been shown to give increased engine efficiency.[214,219]

Nitric oxide emissions with hydrogen fuel are affected by engine variables in much the same way as with gasoline fuel. While anomalously low emissions have been reported,[217,219] other investigations have shown NO_x emissions to be similar to operation with gasoline.[214,215,220] NO_x control can be achieved by water injection or EGR as mentioned previously, and also by very lean operation. Extremely low NO_x emissions can be obtained by restricting equivalence ratios to one half or less, although this then requires a larger engine to achieve the same maximum power.[214-220]

In summary, hydrogen is an attractive fuel from an emissions and economy viewpoint and can be used to fuel conventional-type engines. However, substantial development in vehicular storage systems would be required for large-scale use of hydrogen. Such large-scale use may be required beyond the year 2000 as fossil fuel supplies are depleted.

13.4 Methanol

Methyl alcohol (CH_3OH), or methanol, has been identified as a possible future synthetic fuel and has received considerable attention recently. The present subsection discusses automotive use of methanol fuel with respect to vehicle performance and emissions. Again, the continuous-combustion alternative engines are relatively insensitive to fuel type and are easily designed for operation on methanol. Thus, the discussion is mainly concerned with methanol-fueled, spark-ignited reciprocating engines.

The use of alcohols as motor fuels is not a new idea. The Society of Automotive Engineers held a special meeting on alochol fuels 10 years ago[221] and Bolt's[222] survey presented at that meeting refers to work dating back 50 years. The present discussion is not a comprehensive review of alcohol fuels but rather a brief evaulation of the principal operational, performance and emissions characteristics of methanol-fueled reciprocating engines. Although ethyl alcohol (ethanol) does not now appear to be a cost-effective alternative fuel,[202] much of the present technical discussion is applicable to ethanol as well as methanol.

A comparison of the physical properties of methanol and iso-octane is given in Table 13.2, taken from Reference 223. The energy content per cubic food of stoichiometric methanol-air mixture is about the same as with gasoline so that the engine power will be similar.

One of the major problems associated with the use of methanol is fuel vaporization and distribution characteristics due to methanol's relatively high heat of vaporization and large F/A ratios. Experimental work with methanol indicates that specially designed carburetors and intake manifolds will be required to provide the necessary fuel evaporation and distribution.[222-225] The high heat of vaporization can, in principle, be advantageous in that it results in cooler

TABLE 13.2

Physical Properties of Iso-octane and Methanol

Property	Iso-octane	Methanol
Chemical formula	C_8H_{18}	CH_3OH
Molecular weight	114.22	32.02
Specific gravity (68°F)	0.692	0.792
Stoichiometric A/F	15.1	6.4
Boiling temperature, F°(K)	211 (372)	149 (338)
Latent Heat of vaporation at B.P., Btu/lb (MJ/kg)	117 (0.490)	502 (2.101)
Heating value, Btu/lb (MJ/kg)		
Higher	20,556 (86.047)	9770 (40.897)
Lower	19,065 (79.806)	8644 (36.184)
Energy, Btu/ft^3 of stoichiometric mixture (1 atm, 60°F, LHV, gaseous fuel) (MJ/m^3)	95.5 (3.559)	90.0 (3.354)
Same, liquid fuel	96.6 (3.600)	103.0 (3.839)
Octane No., Research	100	106
Octane No., Motor	100	92

REF 223

intake manifolds and better volumetric efficiencies as well as less compression work in the cylinder.[226] The high heat of vaporization also means that methanol-fueled vehicles cannot be started in environments below 50°F without the addition of a more volatile fuel compound.[223-225] The problem here is vaporization rather than distribution, as indicated by tests where manifold injection of methanol did not improve cold-starting characteristics.[224] It is interesting to note that coal-derived methanol may contain small amounts of higher alcohols[225] which may help alleviate the cold-start problem.

Performance, fuel economy and emissions with methanol have also been recently investigated[223,225,226,228,229] Both single-cylinder-engine experiments and tests with properly carbureted and manifolded-multicylinder engines indicate that the lean misfire limit for methanol occurs at about 20% leaner mixtures than with gasoline. Significant decreases in CO and HC emissions can be obtained by operating with these leaner mixtures. Increased emissions of aldehydes are generally observed along with some reduction in nitric oxide emissions. The principal hydrocarbon emission is methanol, which will be removed with water if an exhaust sample dryer is used. The methanol response on FID analyzers has been found to be between 80% and 100% of saturated hydrocarbon response. Performance and fuel economy (on an energy basis) are generally found to be quite similar to values obtained with gasoline. Since methanol has about half the heating value of gasoline, methanol-fueled vehicles would require twice as large fuel storage tanks for the same range as gasoline. A 1970 vehicle converted to methanol operation and equipped with a special intake manifold and an exhaust-oxidation catalyst has met the 1976-77 Federal Emissions Standards without specific NO_x control except lean carburetion.[223] This vehicle did experience severe cold-start problems until an ether injection system was installed.

Corrosion of lead, magnesium or aluminum fuel tanks or tank coatings has been identified as a severe problem in methanol fuel systems.[226] Corrosion of fuel-injector or carburetor parts can also be a problem.

In summary, with respect to reciprocating engines, we find that methanol is a suitable automotive fuel for the future providing that the cold-start and F/A distribution requirements are included in the engine design. This would require major redesign of existing engine intake systems. Corrosion-resistant materials would have to be used in vehicle fuel tanks and lines including parts of the fuel injector or carburetor. Methanol appears to have the capability for lower emissions (except for aldehydes) than gasoline, principally due to the lower lean misfire limits. Methanol can be burned in continuous-combustion-type engines with little or no difficulty as long as a suitable start-up system is available.

13.5 Methanol-Gasoline Blends

Blends of gasoline with up to 25% methanol have been suggested as gasoline "extenders" for present-day vehicles and are currently receiving increased attention as a result of recent fuel shortages.[230] Like pure methanol, methanol-gasoline blends have long been known as potential fuels, particularly for power boost in racing applications where fuel injection and very rich mixtures are used. In this subsection the fuel mixture and engine performance and emissions characteristics of methanol-gasoline blends are briefly reviewed and assessed with respect to application to spark-ignited reciprocating engines. As with most other alternative fuels, little or no problems would be encountered burning these blends in continuous-combustion engines.

Methanol added to gasoline has the effect of increasing the octane number of the fuel, although this point has been overemphasized. While the research octane number (RON) of modern gasolines is increased about four octane numbers (ON) by addition of 10% methanol, the more severe motor octane number (MON) rating is only increased about 2 ON. (226,231,232) Road octane numbers, which are measured in vehicle tests, are found to be between the RON and MON values, and 10% methanol in unleaded gasoline gives about a 3 ON boost here.[226]

Fuel volatility is also affected by mixing methanol with gasoline. Distillation tests show a more rapid distillation at the lower temperatures for alcohol-gasoline blends compared with gasoline alone.[222,226,232] This despression of the front end of the distillation curve can affect vehicle starting characteristics and may allow for use of heavier components in the base gasoline.[235] The Reid Vapor Pressure of methanol-gasoline blends is higher than either methanol-or gasoline-vapor pressures, and this may indicate an increased tendency for vapor-lock problems.[226,232]

Methanol-gasoline blends are known to be extremely sensitive to the presence of small (~0.1%) quantities of water. The water can cause the separation of the blend resulting in the settling of a water-methanol mixture to the bottom of the storage container (222,225,226,232). The presence of higher alcohols can help alleviate this phase separation, but quantities on the order of several percent are required. While some vehicle-test programs have not shown any problems with phase separation,[233] others have exhibited engine stall attributed to methanol separation in the carburetor bowl.[226] Large-scale use of methanol-gasoline blends would require special water-free bulk distribution, vehicle-storage and carburetor-bowl facilities to minimize moist air intrusion.

Attention has also been given to comparisons of engine performance, fuel economy and emissions between vehicles fueled with gasoline and those fueled with gasoline-methanol blends. If the vehicle carburetor is not adjusted, then the addition of methanol to the gasoline causes a leaner overall stoichiometry. In this case Federal-Test-Cycle evaluations with 10% methanol indicate a 50% reduction in CO, a 10% reduction in NO_x, very little change in unburned hydrocarbons, and a 10% reduction in miles-per-gallon fuel economy.[231] Other road tests also show the CO reduction,[234] but do not give consistent fuel economy results. Both slight improvements[234] and slight losses in fuel economy have been reported.[226] While some road programs do not report driveability problems with methanol blends,[233] other groups (with substantial driveability evaluation experience) report significant driveability degradation with methanol blends.[226,231] Since the addition of methanol without carburetor adjustment does lean the mixture, we would expect lean misfire driveability problems on late-model engines which are already adjusted close to the lean limit. Addition of methanol and adjustment of the carburetor to maintain stoichiometry would undoubtedly compromise the above-mentioned CO emissions reduction. Federal-Test-Procedure data for methanol-gasoline blends is shown in Figure 13.2 and Table 13.3.

Recent evidence indicates that vehicle fuel-tank and distribution systems may experience severe corrosion problems with methanol-gasoline blends.[226]

In summary, methanol-gasoline blends can be used in conventional-type engines provided carburetors are adjusted to maintain driveability. Some reduction in CO emissions may result, but other emissions and fuel economy will not be significantly altered. Careful attention must be given to bulk fuel-distribution and storage systems and vehicle fuel systems to avoid problems of phase separation and corrosion.

13.6 Reformed Fuels

The addition of small amounts of hydrogen to normal fuel systems

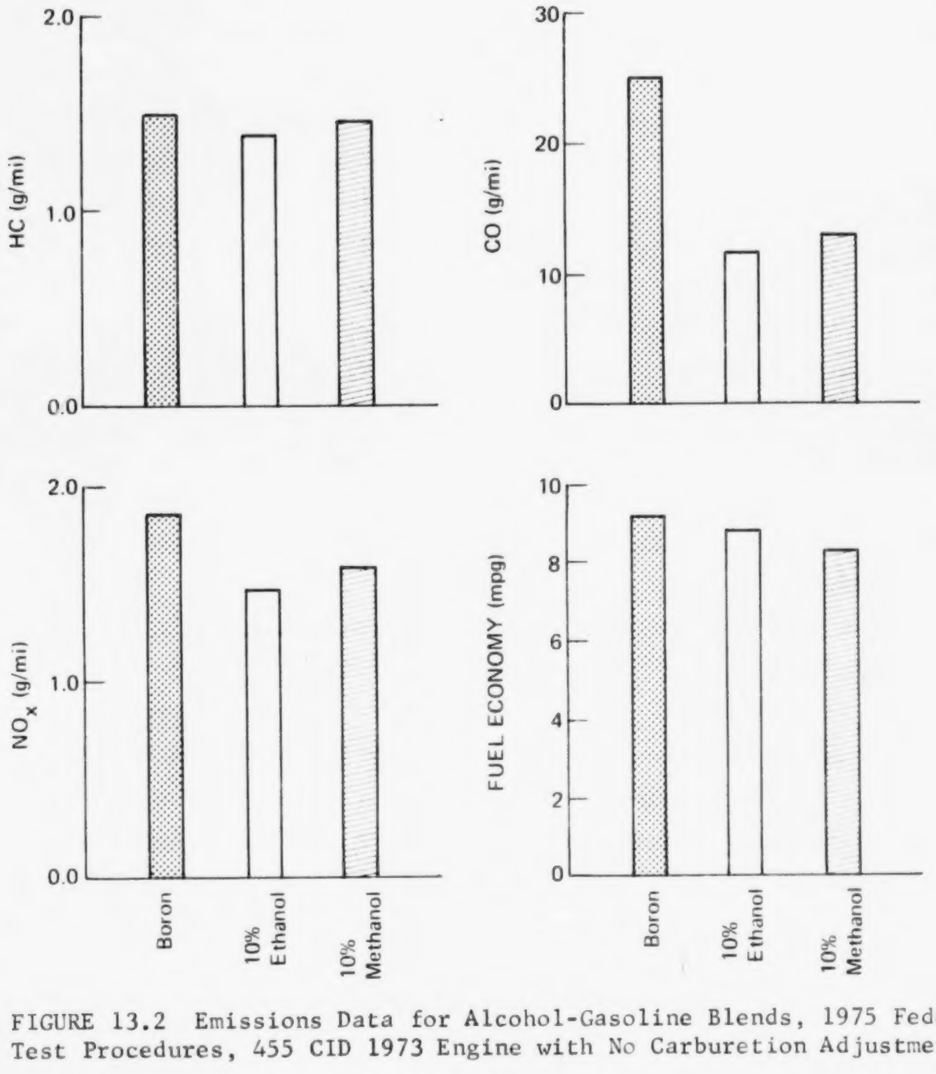

FIGURE 13.2 Emissions Data for Alcohol-Gasoline Blends, 1975 Federal Test Procedures, 455 CID 1973 Engine with No Carburetion Adjustment.

Source: Reference 234

TABLE 13.3

Test Data for 15% Methanol-Gasoline Blend

		Exhaust Emissions, g/mi, Fed. Test Procedure			
		HC	CO	NO_x	Formaldehyde
1967 Car	Gasoline	5.2	83	6.4	0.13
	Gasoline + 15% methanol	3.8	41	8.1	0.20
1973 Car	Gasoline	1.1	21	2.6	0.075
	Gasoline + 15% methanol	1.1	8	1.7	0.10
"1975 Car"	Gasoline	0.10	0.3	2.6	0.002
	Gasoline + 15% methanol	0.10	0.4	2.3	0.004
1977 Federal Standards		0.4	3.4	1.5	-----

	Car		
	1967 (Rich)	1973 (Lean)	"1975" Catalyst Equipped
Gasoline, mpg	14.3	11.2	11.4
Gasoline + 15% methanol, mpg	14.4	10.6	10.9
% Change, mpg	+1	-6	-4
% Change, miles/Btu	+8	+1	+3

Notes

1) Engines - 1967 289 CID V-8, air-gasoline equivalence ratio 0.9
1973 351 CID V-8, air-gasoline equivalence ratio 1.05
"1975" 351 CID V-8, air-gasoline equivalence ratio 1.0

2) Carburetion was adjusted for gasoline-air mixtures and not changed for blends.

3) The "1975" car was equipped with a catalytic converter.

REF 206

(hydrogen-supplemented fuel) can extend the lean misfire limit for spark-ignited, reciprocating engines to quite lean stoichiometry. Such lean mixtures result in significant improvements in engine thermal efficiencies and very low NO_x and CO emissions, but usually result in higher unburned hydrocarbon emissions. One concept for obtaining the required hydrogen involves reforming a portion of the gasoline to hydrogen and carbon monoxide by means of an on-board partial oxidation reforming unit. It is also possible to reform other fuels, such as methanol,[235] to obtain the hydrogen required. In this subsection we review recent work with such hydrogen-supplemented fuel systems.

The effect of adding various amounts of hydrogen to single and multicylinder gasoline-fueled engines has been investigated at General Motors Research Laboratories.[220] Relatively small amounts of hydrogen give dramatic reductions in the lean limit. In a single-cylinder engine, a mixture of 5% H_2 and 95% iso-octane (by mass) extends the lean limit from an equivalence ratio (ϕ) of 0.9 to about 0.7, while 10% H_2 lowers the limit to $\phi = 0.5$. With enough hydrogen added to run at an equivalence ratio of 0.55, NO_x and CO emissions are negligible, and unburned hydrocarbons are about the same as 100% iso-octane at $\phi = 1$. Under the same conditions, thermal efficiency increases from 33% at $\phi = 1$ to 37% at $\phi = 0.55$, while the power output drops about 30%.[220]

Vehicle tests with hydrogen-supplemented fuel were also carried out.[220] In tests with constant hydrogen mass flow, emissions were measured using the Federal Test Procedure (hot start), and the results are shown in Table 13.4 below. Also shown in Table 13.4 are emissions obtained with a fuel-metering system which enabled the relative amount of hydrogen in the fuel to be held constant. The results indicate that lean operation with hydrogen-supplemented fuel does dramatically reduce CO and NO_x emissions, but HC emissions are relatively high.

TABLE 13.4

Federal Test Procedure Emissions with
Hydrogen Supplemented Fuels.

	Emissions (g/mi)	
	Constant Hydrogen Mass Flow	Constant Hydrogen Fraction
NO_x	1.3	0.39
CO	5.6	3.3
HC	2.6	3.1

REF 220

The initial hydrogen-supplemented fuel concept arose at Jet Propulsion Laboratory (JPL) and a large program is underway there.[236] Single and multicylinder engine tests with added hydrogen confirm the results noted above. The current reformer unit is a homogeneous, partial-oxidation type, operating without water feed at 81% efficiency. Development of catalytic-type reformers is also underway. The catalytic reformers operate at much lower temperatures than the homogeneous type and do not have the soot formation tendency. However, they must be warm to function properly and require prevaporized fuel.

Limited vehicle tests with reformer-type products added to the gasoline have been carried out at JPL. While the emissions results were impressive on these tests, it was difficult to determine how much improvement was due to the supplemented fuel and how much was attributable to improved fuel vaporization and distribution due to the use of a special atomizing carburetor. Such carburetors are known to make leaner operation possible.

The reformed fuel concept is an attractive way to achieve the lean operation required for low emissions and good fuel economy. Reformer development and cycle testing are required to fully demonstrate the system. After such demonstration, this concept should be carefully compared with other methods for achieving overall lean operation.

13.7 Other Alternative Fuels

This subsection reviews several additional alternative fuels which have been suggested for their low-emissions potential. These fuels are all blends or emulsions containing a conventional fuel and/or alcohol and water. In general, much less engine test data is available for these compounds than for the previously discussed fuels.

Water and gasoline or distillate combinations in which a surfactant is added to emulisfy the water have been suggested as engine fuels. In distillate combustion such emulsions result in a micro-explosion of the water droplets before combustion because the vapor pressure of the water is greater than the distillate vapor pressure. This micro-explosion should produce finer fuel sprays and may reduce NO_x and soot emissions.[237] Gasoline's higher volatility prevents the micro-explosion phenomenon from occuring in gasoline-water emulsions and any reduction in NO_x would be due to the cooling effect of the water.[237] Also, if the carburetor is not adjusted, metering the gasoline-water mixture instead of gasoline results in leaner engine operation.

Limited emissions data are available from the California Air Resources Board (ARB) cycle tests with "Vareb-10 Fuel", a fuel made up of 57% Indolene, 38% Vareb emulsifier and 5% water by weight. Cold-start test results are given in Table 13.5, taken from Reference 238. CO and NO_x emissions were reduced, but cold-start hydrocarbons increased. The hydrocarbon reactivity ratio also increased with the water gasoline emulsion.

TABLE 13.5

Effect of Vareb-10 on
Cold-Start Emission

Baseline — 1970 Chevrolet E 815472

Test No.	Emissions g/mi HC	CO	NOx	CO_2	Ald.	React. Ratio	Fuel Cons. g Weighted	Cal (1)
10	3.50	39.08	4.65	626	0.091	0.471	1715	1649
12	3.35	36.00	4.78	635	0.076	0.448	1748	1658
14	3.05	24.48	5.43	677	0.067	0.474	1739	1710
Avg.	3.30	33.19	4.95	646	0.078	0.464	1734	1672

Vareb 10

Test No.	Emissions g/mi HC	CO	NOx	CO_2	Ald.	React. Ratio	Fuel Cons. g Weighed (2)	Cal (1)
11	3.53	9.83	2.14	651	0.063	0.582	1684	1600
13	3.79	9.84	2.26	657	0.105	0.569	1884	1616
15A	3.48	9.11	2.08	695	0.092	0.583	1827	1702
Avg.	3.60	9.59	2.16	668	0.087	0.578	1798	1639

(1) Calculated from emissions by carbon balance.
(2) Multiplied by 0.836 to correct for 14.4% H_2O.

REF 238

Homogeneous blends of gasoline, isoprepyl or tertiary butyl alcohol, and water have been patented by Frech and Tazuma of Goodyear Research Laboratories.[239] The blends contain about 40% alcohol, and water is added to the miscible range. It is proposed that these large quantities of alcohol would be obtained by removing propene and isobutene from current refinery streams and converting them to isopropyl alcohol or t-butyl alcohol. Only very limited vehicle-test data is available for these blends. California cycle tests on a 1969 Dodge indicated reductions of 70%-80% in CO, 30%-45% in H/C, and 25%-30% in NO_x. Fuel economy was not measured. Increases of about 3 RON per 10% alcohol are claimed for the blends. More vehicle-test data and an analysis of the refining costs are necessary for a full evaluation of the potential for these blends. In particular, tests on late-model vehicles are not expected to show as large an emissions reduction as noted above.

A water/methanol gasoline blend, in which a surfacant is used to obtain a stable emulsion of the water/alcohol in the gasoline, has been suggested as a emissions reducing fuel.[240] Tests using a 7.5% methanol, 2% surfacant, 0.5% water, 90% gasoline fueled 1973 vehicle (360 CID, A/F = 15.5:1, CR = 8.5:1) quite similar to previously discussed methanol-gasoline blends. The leaning effect reduced CO substantially but HC, NO_x and fuel economy were not significantly changed. The use of a surfactant to increase the water tolerance of methanol-gasoline blends is noteworthy. If such a compound were economically available in large quantities, it might help solve the water sensitivity problem and make the use of gasoline-methanol mixtures more attractive.

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APPENDIX A

Organizations Contacted by Members of the Panel of Consultants on Engine Systems

1.	Ford Motor Co., Dearborn, MI	1/17/74	*John
2.	Chrysler Corp., Detroit, MI	1/17/74	John
3.	Environmental Protection Agency, Ann Arbor, MI	1/23/74	John
4.	Chrysler Corp., Detroit, MI	2/12/74	John
5.	Ford Motor Co., Ann Arbor, MI	2/13/74	John
6.	General Motors Corp., Warren, MI	2/14/74	John
7.	California Air Resources Board, Los Angeles, CA	3/20/74	John
8.	Dresser Industries, Santa Ana, CA	3/21/74	John
9.	Philco-Ford, Newport Beach, CA	3/21/74	John, Newhall
10.	New York City Air Resources Board, New York, NY	3/26/74	John
11.	Curtiss-Wright Corp., Wood-Ridge, NJ	3/27/74	John, Wulfhorst
12.	Texaco, Inc., Beacon, NY	3/28/74	John
13.	Universal Oil Products, Des Plaines, IL	4/16/74	John, Jost
14.	Bendix, Detroit, MI	5/7-8/74	John, Jost
15.	Ethyl Corp., Ferndale, MI	5/7-8/74	John, Jost
16.	Holley Carburetor, Detroit, MI	5/7-8/74	John, Jost
17.	Yanmar Diesel, Osaka, Japan	5/9/74	Wulfhorst

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*Last names of members of the Panel of Consultants on Engine Systems

18.	Toyo Kogyo Co., Ltd., Hiroshima, Japan	5/10/74	Wulfhorst
19.	General Motors Corp., Warren, MI	5/15/74	John, Newhall
20.	Ford Motor Co., Dearborn, MI	5/16/74	John, Newhall
21.	Chrysler Corp., Detroit, MI	6/4/74	John
22.	TACOM, Detroit, MI	6/4/74	John
23.	Questor Corp., Toledo, OH	6/6/74	John
24.	Shell Research Ltd., Thornton, England	6/14/74	John
25.	Ricardo & Co. Engineers, Ltd., Shoreham-by-the-Sea, England	6/17/74	John, Henein, Jost
26.	British Leyland Ltd., Coventry, England	6/18/74	John, Jost
27.	C.A.V., London, England	6/18/74	Henein
28.	Toyo Kogyo Co., Ltd., Hiroshima, Japan	6/18/74	Newhall
29.	Toyota Motor Co., Ltd., Aichi, Japan	6/18/74	Newhall
30.	Honda R&D Co., Ltd., Saitama, Japan	6/19/74	Newhall
31.	Perkins Engine Co., Peterborough, England	6/19/74	Henein
32.	Volkswagenwerk AG, Wolfsburg, W. Germany	6/19/74	John, Jost
33.	Daimler-Benz AG, Stuttgart, W. Germany	6/20/74	John, Henein, Jost
34.	General Motors Technical Center, Warren, MI	6/20/74	Wulfhorst
35.	Japan Motor Vehicle Research Laboratory, Osaka, Japan	6/20/74	Newhall
36.	Nissan Motor Co., Ltd., Tokyo & Yokosuka, Japan	6/20/74	Newhall

37.	Daihatsu Kogyo Co., Ltd., Osaka, Japan	6/21/74	Newhall
38.	Robert Bosch GMBH, Postfach, W. Germany	6/21/74	John, Henein, Jost
39.	Audi, Ingolstadt, W. Germany	6/22/74	John, Jost
40.	Ford Motor Co., Dearborn, MI	7/9/74	Newhall
41.	Gould, Inc., Cleveland, OH	7/9/74	John
42.	General Motors Corp., Warren, MI	8/1/74	John

APPENDIX B

Organizations Contacted by Members of the Panel of Consultants on Alternatives

1.	Environmental Protection Agency, Ann Arbor, MI	1/22-23/74, 3/27/74, 7/2/74	*Bjerklie, Tobias
2.	ACAAPS Review Meeting, Washington, DC	2/11/74	Bjerklie
3.	Chrysler Corp., Detroit, MI	2/12/74, 3/28/74	Bjerklie, McLean, Wilson
4.	Ford Motor Co., Dearborn, MI	2/13/74, 3/28/74	Bjerklie, McLean, Wilson
5.	General Motors Corp., Warren, MI	2/14/74, 3/26/74	Bjerklie, Tobias
6.	Society of Automotive Engineers Meeting, Detroit, MI	2/27/74	Bjerklie
7.	Petro-Electric Motors, Ltd., New York, NY	March 1974	Bjerklie
8.	Massachusetts Institute of Technology, Boston, MA	3/8/74, May 1974	Bjerklie, McLean
9.	Scientific Energy Systems, Watertown, MA	3/8/74	Bjerklie, McLean, Wilson
10.	Thermo-Electron Corp., Waltham, MA	3/8/74	Bjerklie, McLean, Wilson
11.	United Stirling (Sweden) in Boston, MA	3/15/74	Bjerklie
12.	The Hydrogen Economy Miami Energy (Theme) Conference, Miami Beach, FL	3/18-19/74	McLean
13.	Institute of Gas Technology, Chicago, IL	3/25/74, 8/15/74	McLean
14.	Williams Research, Detroit, MI	3/27/74	Bjerklie, Wilson

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*Last names of members of the Panel of Consultants on Alternatives

15.	Exxon Res. & Eng., Linden, NJ	4/3/74	McLean
16.	Brobeck Associates, Berkeley, CA	4/8/74	Bjerklie
17.	Chevron Research Co., Richmond,CA	4/8/74	McLean
18.	University of California (Berkeley) CA	4/8/74	McLean
19.	Jet Propulsion Lab., Altadena, CA	4/9/74	Bjerklie, McLean
20.	Solar, San Diego, CA	4/10/74	Bjerklie, McLean
21.	Steam Power Systems, San Diego, CA	4/10/74	Bjerklie
22.	Bartlesville Energy Research Center (U.S. Bureau of Mines) Barltesville,OK	4/11/74	McLean
23.	Kinergetics, Tarzana, CA	4/11/74	Bjerklie
24.	Philips Petroleum, Bartlesville, OK	4/11/74	McLean
25.	Zwick Co., Santa Ana, CA	4/11/74	Bjerklie
26.	Jay Carter Enterprises, Burkburnett,TX	4/12/74	Bjerklie
27.	NASA Lewis Research Center, Cleveland, OH	4/12/74	McLean
28.	DAUG, Stuttgart, W. Germany	5/15/74	Bjerklie
29.	British Railway Tech. Ctr., Derby, England	5/16/74	Bjerklie
30.	Philips Research Labs., Eindhoven, Holland	5/20/74	Bjerklie
31.	United Stirling, Malmo, Sweden	5/21/74	Bjerklie
32.	MAN-MWM, Augsburg, W. Germany	5/22/74	Bjerklie
33.	Volkswagenwerk AG, Wolfsburg, W. Germany	5/24/74	Bjerklie
34.	Princeton University, Princeton, NJ	8/16/74	McLean
35.	Goodyear Research Labs., Akron, OH	8/16/74	McLean

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